Comparative multiscale investigations of material removal behaviors of SiCp/5083Al, SiC ceramic and 5083Al alloy by single scratch tests

Xu Zhao1,2, Yadong Gong1, Ming Cai1 and Bing Han2

1 School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, People’s Republic of China
2 School of Mechanical Engineering and Automation, University of Science and Technology Liaoning, Anshan, 114051, People’s Republic of China

E-mail: gongyd@mail.neu.edu.cn

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Abstract
To gain a deep insight into the material removal mechanism of high volume fraction SiCp/Al during a grinding process, comparative multiscale investigations of material removal behaviors of 50 vol% SiCp/5083Al, bulk SiC and bulk 5083Al are presented by single scratch tests. Scratch mechanical properties including scratch force, friction coefficient and AE signal, as well as cross-sectional profile including residual scratch depth and material removal ratio are introduced to measure material removal behaviors at macroscale and mesoscope. Moreover, surface morphology of scratch grooves with help of SEM micrographs and explanatory model of material removal mechanisms are used to understand material removal evolution at microscale. It has demonstrated that at macroscale and mesoscope material removal behaviors of SiCp/5083Al are similar to that for 5083Al, but different from that for SiC, at microscale essentially different from that for 5083Al and SiC. Normal force (scratch depth) has significant influence on material removal behaviors, a sufficiently low scratch depth could achieve ductile removal of particles SiC resulting in a comparatively good surface for SiCp/5083Al, otherwise, the reverse. The work findings provide a critical insight of the material removal mechanism for SiCp/Al by considering coupling effects of particles SiC and matrix Al, and critical information for improving grinding quality.

1. Introduction

SiC reinforced aluminum matrix (SiCp/Al) composites possess superior mechanical and tribological properties, such as outstanding strength-to-weight ratio, high resistance of wear and corrosion, low thermal expansion. The application of SiCp/Al composites is increasing in high technology industries, especially 40 vol%–50 vol% SiCp/Al composites in the optics industry. Dimensional accuracy and surface finish of SiCp/Al composites is commonly achieved via the grinding process. However, the poor grindability of high volume fraction SiCp/Al composites impedes wide-spread replacement of traditional materials. Understanding in material removal behavior of high volume fraction SiCp/Al composites is extremely necessary for optimization of grinding process to improve grinding quality [1].

The smallest element of the grinding process is a single grit which is one of numerous grits bonded on a grinding wheel, so single-grit scratch tests are commonly conducted experimentally as a simplified analogy of grit-workpiece interactions to investigate material removal mechanism in the grinding process [2]. Deeper understanding of brittle and hard material removal process was achieved via numerous traditional scratch tests [2–8] and ultrasonic vibration-assisted scratch tests [9–12]. Single-grit scratch tests were also widely utilized to analyze ductile material removal mechanism at microscale during grinding [13–20]. Besides, a few researchers carried out single grit scratch tests to investigate SiCp/Al composites removal characteristics. Feng et al [21]
investigated differences in scratching force, scratching morphology and friction coefficient of SiCp/Al composites in between traditional scratch tests and ultrasonic vibration-assisted scratch tests, the results shown that scratch force and friction coefficient were smaller, but the quality of scratch surface was better in ultrasonic vibration-assisted scratch tests, compared to traditional scratch tests. Zha et al. [22] adopted the similar methods to investigate scratch characteristics of high-volume fraction SiCp/Al composites, the same conclusions were obtained, in addition, the material removal processes in both traditional scratch tests and ultrasonic vibration-assisted scratch tests were briefly described and compared. Zheng et al. [23] conducted the similar investigations and obtained the same results, but the material removal modes of SiC particles were deeper analyzed in both traditional scratch tests and ultrasonic vibration-assisted scratch tests, the integrity of SiC particles was better in ultrasonic vibration-assisted scratch tests. Zhao et al. [24] also conducted the single-grit scratch experiments of high volume fraction SiCp/Al composites, but which only exhibited SEM images of the scratch surface aiming to verify their numerical analysis results. Gu et al. [25] established a prediction model for the single-abrasive-grain grinding force, as well a prediction model for the multi-abrasive –grain grinding force via the support vector machine prediction method. Wang et al. [26] and Liu et al. [27] all investigated the probability of ductile regime machining of SiC particles in SiCp/Al. Besides, Wang et al. [28] analyze the softening mechanism of 2 vol. % nano-SiCp/Al-12Si composites via isothermal heat compression test, and concluded that the softening mechanism mainly includes the cross slip, clipping of dislocation, and untangling of three-dimensional dislocation network.

In previous works, all of investigations dealing with material removal behaviors of SiCp/Al composites by utilizing the single-grit scratch tests only focused on SiCp/Al composites, but not concerned coupling effects of scratch characteristics of reinforced particle SiC and aluminum alloys on material removal behaviors of SiCp/Al composites as a two-phase material. The inherent inhomogeneity of hard SiC particles and soft aluminum matrix is the major factor that affects the overall grindability of SiCp/Al composites, so a systematical comparison of material removal behaviors between SiCp/Al composites and SiC ceramic as well as aluminum is requisite. In the paper, single-grit scratch tests are conducted on 50 vol.% SiCp/Al, SiC ceramic and aluminum, scratch mechanical properties including scratch force, friction coefficient and AE signal, as well as cross-sectional profile including residual scratch depth and material removal ratio are used as indicators to identify and compare material removal behaviors at macroscale and mesoscope, SEM micrographs of scratch grooves and descriptive models explaining the scratch surface phenomena and underlying material removal mechanisms are used to understand evolution of material removal at microscale. Via comprehensive comparisons of material removal behaviors of SiCp/Al, SiC and Al during single scratch tests, the paper presents the critical information about the effects of the matrix material and reinforced material on material removal mechanisms of SiCp/Al.

2. Materials and methods

2.1. Specimens preparation

In order to satisfy the urgent request of the opto-mechanical structure for grinding quality of SiCp/Al composites (40vol%-50vol%) which is a two-phase material composed of 5083Al and SiC, material removal and surface defect mechanism are analyzed via scratch tests on 50vol% SiCp/Al composites, 5083Al and SiC.

This research work adopt 50 vol.% SiCp/5083Al composites widely used in optics industry as the sample material, in which the average size of commercial black SiC particles is 20 μm. Powder metallurgy technique is utilized to produce the composite, as follow: 5083Al powders and SiC particles are firstly mixed sufficiently at 27:32 ratio of weight, this process takes 10 h via ball milling at 150 rpm; then cold isostatic compaction of the mixture is followed in a mould; next, the mixture is heated under 120 Mpa at 753 K for 2 h by using the vacuum furnace HIP-200, and followed by furnace cooling; finally, the composite is subsequently extruded with an extension ratio of 20:1 at 773 K, and followed by being hold at 833 K for 3 h and artificially aged at 423 K for 18 h. The specimen is machined into a rectangle with dimensions of 40mm length, 35mm width and 15mm height, then is polished consecutively with diamond paste of 20 μm, 14 μm, 7 μm, 3 μm and 1 μm grain size to get a defect-free surface. The microstructure of the composites is presented in figure 1.

Commercial black SiC produced by a domestic SiC ceramics industry company is utilized as the SiC specimen material, the chemical composition of commercial black SiC is shown in table 1 the specimen is machined into a rectangle with dimensions of 40mm length, 35 mm width and 15 mm height, then is polished successively with 10 μm, 5 μm, 3 μm diamond powder and 0.04μm silica suspension liquid to get a very smooth surface.

The material used as the 5083Al specimen is 5083 aluminum alloy produced by a domestic aluminum industry company, the chemical composition of thick plate is shown in table 2. To get a defect-free surface, the specimen is firstly manually grinded successively by 400#, 800#, 1200#, 1500# sandpaper, and then polished.
successively with silk + W2.5 polishing paste, woolen + W0.5 polishing paste. The basic mechanical properties of SiCp/Al composites, SiC and 5083Al are listed in table 3.

2.2. Single grit scratch tests procedure

The single-grit scratch tests are performed on MFT-4000 Scratch Tester (Lanzhou Huahui Instrument Technology Co., Ltd, Lanzhou, Gansu, China) whose major technical indicators are listed in table 4 by using a conical diamond indenter with cone angle 120° and tip radius 20 μm (figure 2(a)). As shown in figure 2(b), the indenter is introduced into the specimen with a normal down force which increases monotonically from 0 N to 100 N at a rate of 50 N min \(^{-1}\) exerted via the automatic loading device, while the specimen is moving linearly at a constant speed of 10 mm min \(^{-1}\). According to T T Öpöz [20], the scratch depth is more influential in the investigation of material removal behaviors than scratch speed, so scratch speed is not selected as a variable. During the scratch, a scratch groove of increasing depth is generated, and the tangential scratch force and acoustic emission (AE) signals are recorded, the friction coefficient curve under the specific conditions is obtained by computing the ratio of the tangential scratch force to normal force.
2.3. Measurements

After the scratch, ZEISS Ultra Plus Field Emission Scanning Electron Microscope (SEM, ZEISS, Jena, Thuringia, Germany) is used to observe the scratch surface morphology which reveals different material removal behaviors at microscale. According to I D Marinescu [12], ploughing, (ductile) cutting and (fracture) cracking are the three modes of material removal by grit cutting edges during grinding and scratching. In order to investigate differences in material removal characteristics of SiCp/5083Al, 5083Al and SiC under different scratch depths, the material removal ratio is introduced to determine the prominent characteristics of material removal, the material removal ratio, \( f \), is described as follow [29]:

\[
f = \frac{A_g - A_p}{A_g}
\]

where \( A_g \) is the groove cross-sectional area, \( A_p \) is the total pile-up cross-sectional area, \( 0 < f < 1 \) if a combination of ploughing and ductile removal (figure 3(a)), \( f = 1 \) if ideal ductile removal, and \( f > 1 \) if fracture removal (figure 3(b)).

The 3D profiles of the scratch grooves are measured by VHX-1000E super-depth microscope (KEYENCE, Higashiyodogawa Ward, Osaka, Japan), then 2D cross-sectional profiles of the scratch grooves are extracted to measure the residual scratch depth and curve information of the grooves and pile-up, which are imported into Matlab R2014a to calculate the groove and pile-up cross-sectional areas at a certain point by using the numerical integration method. The samples of 3D profile and 2D cross-sectional profile of the scratch grooves are shown in figure 4.

Therefore, the machinability reflected by the tangential scratch force, friction coefficient and AE signals, material removal characteristics indicated by the scratch depth and material removal ratio, and evolution of material removal behaviors at microscale revealed by the scratch surfaces morphology are analyzed to reveal the differences in material removals behaviors of SiCp/5083Al, 5083Al and SiC during single scratch tests.

| Loading Mode | Automatically Load |
|--------------|--------------------|
| Loading range | 0.25 N ~ 200 N automatic loading continuously, the precision is 0.25 N |
| Scratch length | 2 mm ~ 40 mm |
| Scratch velocity | 10 mm min\(^{-1}\) |
| Loading rate | 1 N min\(^{-1}\) ~ 100 N min\(^{-1}\) |
| Measuring range | 0.5 \( \mu \)m ~ 30 \( \mu \)m |
| Friction measuring range | 10 N ~ 100 N, precision is 0.25 N |

Table 4. The major technical indicators of MFT-4000 Scratch Tester [24].

Figure 2. Single grit scratch tests procedure: (a) MFT-4000 Scratch Tester; (b) tests details.
3. Results and discussion

3.1. Scratch mechanical properties
The scratch mechanical properties including the scratch force, friction coefficient and AE signals reflect material removal behaviors during the scratch process at macroscale and mesoscale. For a certain material, the scratch depth varies synchronously with the normal force, so incremental change in the normal force can be regarded as the representation of that in the scratch depth. The measured tangential scratch force, friction coefficient and AE versus the normal force are presented in figures 5(d)–(f), respectively. In addition, SEM images of scratch tracks on SiC, SiCp/5083Al and 5083Al are also provided in figures 5(a)–(c), respectively, aiming to intuitively exhibit the relevancy between the scratch surface morphology and scratch mechanical properties.

Figure 5(d) presents the variations of the tangential scratch forces for SiC, SiCp/5083Al and 5083Al under continuously increasing normal force. For SiC, the tangential scratch force increases approximately linearly at a very low rate with slight fluctuations under lower normal forces of 0–4 N, and increases more or less linearly at a higher rate with more fluctuations under higher normal forces of 4–40 N, but above a certain normal force of 40 N, it increases nonlinearly and fluctuates more largely as the normal force increases, especially when the normal force is larger than 70 N an increase slope and severe fluctuations visibly occur. The variation of tangential scratch force for brittle SiC can be explained by the SEM image of the scratch track on SiC shown in figure 5(a).

At the beginning of the scratch groove, a comparatively smooth surface with few cracks that indicates a ductile removal mode is observed. As the normal force increases to 4 N, brittle removal features such as cracks emerge on the scratch groove. With further increase of the normal force to 40 N, large brittle peeling of materials which leads to nonlinear increase and more fluctuations of the tangential scratch force can be observed. Larger brittle peeling of materials occurring when the normal force is over 70 N leads to rapid increase and severe fluctuations of the tangential scratch force, at this stage the tangential scratch force for SiC first exceeds that for SiCp/5083Al and 5083Al.

For SiCp/5083Al and 5083Al, the tangential scratch forces increase more or less linearly with the normal force in the similar trend during the whole scratch process, but the tangential scratch force and its increase rate
for 5083Al are all larger than that for SiCp/5083Al. On the other hand, it is worth noting that the tangential scratch force for 5083Al increases smoothly, while that for SiCp/5083Al fluctuates more prominently. The characteristics of tangential scratch forces for SiCp/5083Al and 5083Al correspond to the SEM images of the scratch tracks shown in figures 5(b) and (c). Figure 5(c) presents a very smooth scratch groove surface for 5083Al corresponding to the typical ductile metal removal mode, so its tangential scratch force increases smoothly. However, figure 5(b) shows a comparatively coarse scratch surface, irregular pile-ups as well as a narrower and shallower scratch groove, which explain the phenomenon that tangential scratch force for SiCp/5083Al increases at a smaller rate with more fluctuations and a smaller magnitude than that for 5083Al, due to presence of reinforced particles SiC. Overall, the magnitudes of the scratch grooves shown in figures 5(a)–(c) determine the magnitudes of the tangential scratch forces shown in figure 5(d) under the regular scratch conditions, namely largest magnitudes for 5083Al and smallest magnitudes for SiC. Moreover, the characteristics of the

Figure 5. Diagrams of SEM images of scratch tracks on (a) SiC, (b) SiCp/5083Al and (c) 5083Al, (d) tangential scratch force, (e) friction coefficient and (f) intensity of acoustic emission (AE) under increasing normal force.
scratch force and scratch groove surface for SiCp/5083Al is similar to those for 5083Al at mesoscale, but different to that for brittle SiC.

Friction coefficient is another one of vital scratch mechanical properties and is often used to reflect the grit-specimen contact status and material removal features, which is the ratio of the tangential scratch force to the normal force. The variations of friction coefficients for SiC, SiCp/5083Al and 5083Al under the continuously increasing normal force are shown in figure 5(e). It can be seen that the friction coefficient for SiC is significantly lower than that for SiCp/5083Al and 5083Al, and the characteristics of the friction coefficient for SiCp/5083Al is similar to that for 5083Al, but presence of SiC particles leads to lower magnitude and more fluctuations of friction coefficient for SiCp/5083Al compared to 5083Al.

For SiC, at low normal forces of 0–4 N, the variation of friction coefficient is accord with the feature of ductile removal, namely the friction coefficient first increase sharply and then stays stable oscillation, but above normal force 4 N, the friction coefficient increases with fluctuations as the normal force increases due to initiation and propagation of cracks on the scratch groove surface shown in figure 5(a), before long, a relatively stable status of friction coefficient is observed during normal force 16–40 N, after that, the friction coefficient again increases nonlinearly with larger fluctuations because of large brittle peelings of materials presented in figure 5(a), finally the normal force of over 70 N leads to an abrupt increase and severe fluctuations of the friction coefficient corresponding to larger brittle peelings of materials shown in figure 5(a).

For 5083Al, the friction coefficient first increases with increasing normal force, then remains approximately constant (≈0.48) under the normal force of above 23 N.

For SiCp/5083Al, the friction coefficient first increases with more and larger fluctuations during longer span of the normal force compared to 5083Al, but after a certain normal force (≈36 N), it stays a stable tendency to extremely slowly increase. These indicate that reinforced particles SiC induce the larger critical normal force for a stable status and more and larger fluctuations of the friction coefficient for SiCp/5083Al compared to 5083Al.

Based on the suggestion given by Bowden and Tabor [30] that the friction can be subdivided into adhesion term \( \mu_a \) and ploughing term \( \mu_p \), appropriate adjustments of the friction coefficients for SiC, 5083Al and SiCp/5083Al are done.

For a single-phase brittle material such as SiC, friction coefficient during a scratch test can be given by

\[
\mu = \begin{cases} 
\mu_a + \mu_p & \text{for ductile removal mode} \\
\mu_a + \mu_1 & \text{for brittle removal mode}
\end{cases}
\]  

where \( \mu_a, \mu_p \) and \( \mu_1 \) are the components caused by adhesion, ploughing and fracture, respectively. According to Zhang [31], the combination of adhesion and ploughing friction coefficient can be described

\[
\mu_a + \mu_p = \frac{k_1 A_p H_v}{F_N}
\]  

where \( k_1, A_p \) and \( F_N \) are a geometric factor of the indenter, the cross-sectional area of the scratch groove and the normal force, respectively, and \( H_v \) is the Vickers indentation hardness determined by

\[
H_v = \frac{2F_N \sin (2\theta)}{d_1^2}
\]  

where \( \theta \) and \( d_1 \) are the apex angle of the indenter and the mean diagonal of the indentation.

According the Griffith equation [32], the friction coefficient component contributed from SiC fracture can be given by

\[
\mu_1 = K_{1c} \cdot \frac{A_p}{F_N}
\]  

where, \( K_{1c} \) is the fracture toughness of SiC.

so the friction coefficient for SiC is then given by

\[
\mu = \begin{cases} 
\mu_a + \mu_p & \text{for ductile removal mode} \\
\mu_a + \mu_1 & \text{for brittle removal mode}
\end{cases}
\]

For a single-phase ductile material such as 5083Al alloy, friction coefficient during a scratch test can be given by

\[
\mu = \mu_a + \mu_p = 2k_1 \sin (2\theta) \frac{A_p}{d_1^2}
\]  

where \( \mu_a \) and \( \mu_p \) are the components caused by adhesion and ploughing, respectively.
For a multi-phase material such as SiCp/5083Al, friction coefficient during a scratch test can be written as follows

\[ \mu = \mu_s + \mu_p + \mu_f \]  

where \( \mu_s, \mu_p \) and \( \mu_f \) are the components caused by adhesion, ploughing and SiC particles fracture, respectively. According to Zhang [31], the friction coefficient component contributed from SiC particles fracture can be determined by

\[ \mu_f = k_f \frac{F_p}{A_p} \] 

where, \( k_f, f, \alpha \) and \( K_{1cp} \) are a geometric factor, the volume fraction, mean size and fracture toughness of the reinforced particle SiC, respectively.

So, the friction coefficient for SiCp/5083Al is then given by

\[ \mu = \mu_s + \mu_p + \mu_f = 2k_1 \sin(2\theta) \frac{A_p}{d_1^2} + k_2 f v_1cp d_{1/2} \frac{A_p}{F_N} \]

Through comparisons of friction coefficient expressions for SiC, 5083Al and SiCp/5083Al, namely equations (6), (7) and (10), further understanding of friction coefficients for the above three materials can be achieved. The following discussions are based on the same geometric parameters of the indenter, \( k_1 \) and \( \theta \).

According to equation (6), the friction coefficient of SiC in ductile removal mode is the combination of adhesion term \( \mu_s \) and ploughing \( \mu_p \) and \( \frac{\alpha}{d_1^2} \) for SiC is far less than that for 5083Al and SiCp/5083Al under the same normal force, so the friction coefficient for SiC stays stable at a far lower magnitude than that for 5083Al and SiCp/5083Al in ductile removal mode (normal force 0–4N) shown in figure 5(e). As the normal force increases, the brittle removal mode plays the leading role, so the friction coefficient of SiC becomes the combination of adhesion term \( \mu_s \) and fracture term \( \mu_f \). The fracture term \( \mu_f = (K_{1cp} \frac{A_p}{F_N}) \) induces a rapid increase and more fluctuations due to initiation and propagation of cracks, but the magnitude of the friction coefficient for SiC remains far lower than that for 5083Al and SiCp/5083Al until large brittle peelings of material appear, large brittle peelings of materials lead to sharp increase and oscillation of the fracture term \( \mu_f \) which now plays a decisive effect on the friction coefficient, consequently, the friction coefficient for SiC abruptly increases over that for 5083Al and SiCp/5083Al, and severely fluctuates, which can be seen in figure 5(e).

According to equations (7) and (10), the difference in constituents of the friction coefficients for 5083Al and SiCp/5083Al is SiC particles fracture term \( \mu_f \). As a result from presence of reinforced particles SiC. For SiCp/5083Al, the combination of adhesion term \( \mu_s \) and ploughing \( \mu_p \) plays a dominant role in the friction coefficient during the overall scratch process, so the variation of friction coefficient for SiCp/5083Al is similar to that for 5083Al, but the improvements of hardness and elastic modulus of the matrix material 5083Al induced by presence of reinforced particles SiC lead to a fact that \( \frac{\alpha}{d_1^2} \) for SiCp/5083Al is less than that for 5083Al under the same normal force, so the friction coefficient for SiCp/5083Al has a smaller magnitude than that for 5083Al, furthermore, the SiC particles fracture term \( \mu_f \) also plays other effects on the variation of friction coefficient, such as more and larger fluctuations. The above interpretation can be supported by the variation curves of the friction coefficients for 5083Al and SiCp/5083Al shown in the figure 5(e).

In addition to the scratch force and friction coefficient, AE is also measured to monitor the state of material removal process. As shown in figure 5(f), AE for SiC remains high when the normal force is above a certain value (about 40 N), which indicates that brittle removal of SiC is then very severe and large brittle peelings of materials also appears. But AE for 5083Al and SiCp/5083Al remain low during the whole scratch process, which reveals the ductile removal characteristics for SiCp/5083Al at macroscale, which is similar for 5083Al. To further investigate differences in AE for SiCp/5083Al and 5083Al, enlarging views of AE for SiCp/5083Al and 5083Al are illustrated in figure 6, which presents that AE for SiCp/5083Al is larger that for 5083Al under some normal forces, that is an evidence in existing of brittle fracture of reinforced particles SiC. For 50 vol% SiCp/5083Al, brittle fracture of reinforced particles is theoretically widespread after a certain normal force, however, absorption of the matrix material 5083Al results in a low magnitude of AE for SiCp/5083Al. Therefore, it can be deduced that the matrix material 5083Al improves the plasticity and scratch characteristics of reinforced particles SiC at macroscale and mesoscope.

Overall, noticeable influences of the normal force on the scratch mechanical properties for 50 vol% SiCp/5083Al, 5083Al and SiC are noted, the tangential scratch force and friction coefficient for 50 vol% SiCp/5083Al, 5083Al and SiC all increase with increasing normal force. Among these three materials under the same normal force, 5083Al exhibits the highest magnitudes and rates of the tangential scratch force and friction coefficient, while SiC shows the lowest ones until larger brittle peelings of material lead to rapid increase and severe fluctuations of the tangential scratch and friction coefficient. The scratch mechanical properties for SiCp/
5083Al are similar to that for 5083Al at macroscale, including scratch force, friction coefficient and AE signal, but presence of reinforced particles SiC results in higher hardness and smaller groove cross-sectional area of SiCp/5083Al thus leading to lower magnitudes and rates of the tangential scratch force and friction coefficient compared to 5083Al. On the other hand, plasticity and scratch characteristics of reinforced particles SiC are improved by the matrix material 5083Al.

Furthermore, grit–particle interactions theoretically influence scratch force and AE signal, but no significant fluctuation of scratch force and AE signal is noted. This may be due to very small inter particle distance in the 50%vol SiCp/Al composite and insufficient frequency and precision of the data acquisition system.

### 3.2. Cross-sectional profile creation of the scratch groove

The cross-sectional profiles of scratch grooves for SiC, SiCp/5083Al and 5083Al by single scratches exhibit different characteristics. The residual scratch depth and material removal ratio are analyzed for cross-sectional profiles of scratch grooves. Figure 7 shows variations of the residual scratch depths for SiC, SiCp/5083Al and 5083Al under increasing normal force. Obviously, the residual scratch depths for these three materials all increase with the normal force increasing, but their magnitudes and curves are different. The magnitudes of residual scratch depths are ranked under the same normal forces thus: 5083Al > SiCp/5083Al > SiC, which is consistent with the magnitude rank of the tangential scratch force and friction coefficient mentioned in section 3.1.

For SiC, at the start of the scratch (normal force 0–4 N), the residual scratch depth stays a extremely low magnitude of 0–0.4 μm, when the material removal is in a ductile or ductile-brittle coexisting removal stage. After the normal force reaches a value higher than 4 N, the residual scratch depth increases significantly with increasing normal force at a high growth rate, its variation trend is nonlinear, and more and severer fluctuations that caused by more and larger brittle cracks and peelings of materials appear as the normal force increases, which indicates that the material removal switches to the brittle removal stage.
For 5083Al, the residual scratch depth approximately linearly increases with increase of the normal force during the whole scratch process.

For SiCp/5083Al, according to the curve growth rate, it is obvious that there are two stages in variation of residual scratch depth. At the first-stage (normal force 0–36 N), the residual scratch depth with respect to the normal force shows a good linear relation with few fluctuations and a relatively high growth rate, but at the second-stage (normal force 36–100 N), the residual scratch depth increases more or less linearly at a lower growth rate with more and severer fluctuations, which attribute to greater influence of reinforced particles SiC on the hardness enhancement of the matrix material with increasing normal force. On the whole, the characteristics of the residual scratch depth for SiCp/5083Al are similar to that for 5083Al, especially at the first-stage, but at the second-stage exhibits more and more influences of reinforced particles SiC with increasing normal force.

Material removal ratios, \( f \), variations with respect to residual scratch depth for SiC, SiCp/5083Al and 5083Al are shown in figure 8, the material removal ratio can quantify the material removal characteristics and its definition and measurement method are mentioned in section 2.3. As shown in figure 8, the material removal ratio for SiC increases with increase of the residual scratch depth, however, that for SiCp/5083Al and 5083Al decrease with increasing residual scratch depth. Moreover, material removal ratio for SiC is significantly highest among these three materials, and that for SiCp/5083Al is obviously higher than that for 5083Al at the same residual scratch depth.

For SiC, the material removal ratio shows a logarithmic increase and seems scattered highly due to brittle removal mode in the most range of the residual scratch depth considered. The trend of a logarithmic increase of the material removal ratio for brittle material attributes to rapid increase of brittle cracks and large peelings of material as the residual scratch depth increases. At the initial stage of the scratch where the residual scratch depth varies from 0 to 0.4 \( \mu \text{m} \), the material removal ratio retains less than 1, 0 \(< f < 1 \) indicates that ploughing and ductile cutting occur. After the residual scratch depth reaches a certain value greater than 0.4 \( \mu \text{m} \), the material removal ratio is constantly greater than 1, which demonstrates that material removal mode moves to brittle removal.

For SiCp/5083Al and 5083Al, it is obvious in figure 8 that the material removal ratio variation for SiCp/5083Al is similar to that for 5083Al, and their material removal ratios all show a logarithmic decrease and are all lower than 1, 0 \(< f < 1 \) indicates that ploughing and ductile cutting occur. The reason of a logarithmic decrease in material removal ratio for ductile and ductile-like materials seems to be that cutting edges of the grit act blunter due to larger engaging width (which is proportional to the residual scratch depth) comparing with smaller engaging width. Therefore, it can be inferred that the material removal behavior for SiCp/5083Al is similar to that for 5083Al in ductile removal mode at macroscale, although it includes 50 vol\% SiC particles. On the other hand, presence of SiC particles induces a higher material removal ratio of SiCp/5083Al compared to 5083Al.

Overall, based on the cross-sectional profile characteristics including residual scratch depth and material removal ratio, the material removal behavior for SiCp/5083Al is similar to that for 5083Al in ductile removal mode at macroscale, while presence of SiC particles results in lower magnitude of residual scratch depth and larger magnitude of material removal ratio for SiCp/5083Al. The cross-sectional profile characteristics of the scratch groove is consistent with the variation characteristics of the scratch mechanical properties for SiC, SiCp/5083Al and 5083Al, the cross-sectional profile characteristics and the scratch mechanical properties are the result and real-time mechanical response of the single-grit scratch, respectively.
3.3. Surface morphology of scratch grooves

In preceding sections, material removal behaviors regarding scratch mechanical properties and cross-sectional profile characteristics of scratch grooves have been investigated, such investigations do represent the material removal mechanism at macroscale and mesoscope, but not at microscale. Here, investigations of material removal behaviors will emphasize on surface morphology of scratch grooves at microscale.

Figure 9 shows SEM images of the scratch groove for SiC with increasing normal force. It can be seen that material removal mechanism is greatly dependent on the normal force, as presented in Figure 9(a). At the initial scratch stage, a small enough normal force ranging from 0N to 4N results in ductile removal, which can be identified by the smooth scratch groove surface without cracks, but brittle features begin to occur while the normal force is becoming over 4N, as shown in Figure 9(b). As illustrated in figures 9(a) and (d), with continuous increase of the normal force, brittle features become more serious, lateral and radial cracks rapidly propagate and intersect, which lead to material spalling, moreover, the extended radial cracks distribute on both sides of the scratch groove in an angle ranging from 30° to 45° to the scratch direction, because the orientation of the cracks is affected by both the material structure and the boundary of compression and tension. The influence of the boundary of compression and tension gradually rise as scratch depth increases, so the cracks deflected near the boundary of compression and tension as the indenter moved forward (about 30° to 45° to the scratch direction, as illustrated in figure 10). When the normal force increases further, larger peelings of material and cracks propagation can be recognized at the final scratch stage in figures 9(a) and (c). Generally, brittle material removal is the primary material removal mode for SiC during the scratch test, but ductile material removal can be obtained if the normal force is small enough. The material deformation and removal behavior are dominated by both the external factors including the grit shape, scratch process parameters, etc, and the intrinsic factors such as material structure and interior defects.

Figure 11 depicts SEM images of the scratch groove for 5083Al with increasing normal force. It is obvious that its material removal is in ductile removal mode, consisting of ploughing and ductile cutting, which is illustrated by the smooth scratch groove surface and pile-up during the whole scratch process in figures 11(a) and (b). Generally, brittle material removal is the primary material removal mode for SiC during the scratch test, but ductile material removal can be obtained if the normal force is small enough. The material deformation and removal behavior are dominated by both the external factors including the grit shape, scratch process parameters, etc, and the intrinsic factors such as material structure and interior defects.

Figure 9. SEM images of scratch groove for SiC with increasing normal force: (a) the overall scratch groove, (b) magnified view of the red region on the initial scratch surface, (c) magnified view of the red region on the final scratch surface, (d) magnified view of the red region on the middle scratch surface.
phenomenon, namely a smooth scratch groove surface without any defects. As shown in figure 11(a), the pile-up area becomes increasingly large as the normal force increase, while more and more accumulated materials which could not be removed surrounds the girt.

Figure 12 shows SEM images of scratch groove for SiCp/5083Al with increasing normal force, including the overall scratch groove (figure 12(a)), magnified micrographs of the scratch surface at different scratch stages (figures 12(b)–(d)), as well as various magnified micrographs of the identified scratch phenomena (figures 12(e) and (f)). It is reasonable to assume that material removal behaviors for SiCp/5083Al is similar to that for 5083Al at macroscale and mesoscope, which is demonstrated by the SEM images of the overall scratch grooves for SiCp/5083Al in figure 12(a) and 5083Al in figure 11(a), but at microscale, differences in material removal remove behaviors for SiCp/5083Al and 5083Al significantly exist, the description and explanation of the scratch surface morphology for SiCp/5083Al at microscale are as follow.

At the initial stage of the scratch groove shown in figure 12(b), a comparatively smooth surface is generated, SiCp/5083Al shows predominantly ductile behaviors characterized by plastic flow of both soft Al matrix and hard SiC particles, the plastic deformation of SiC particles is characterized as dislocations at this moment. As the normal force increases, partly SiC particles at the edges of the scratch groove are pressed out, which is related to the fact that pipe-ups of the scratch groove for SiCp/5083Al are coarse and disturbed (figure 12(a)), while that for 5083Al are smooth and regular (figure 11(a)).

With further increasing normal force, rise of thermos-mechanical stress on the scratch surface induces change of material removal behaviors from predominantly ductile (figure 12(b)) to predominantly brittle mixed
with ductile (figures 12(c) and (d)), predominantly brittle removal behaviors are characterized by crack initiation and propagation, which result in the scratch surface disruption, such as brittle fracture of SiC particles, crack (tear) of continuous Al matrix and SiC-Al interfacial debonding, cavities, etc, as shown in figures 12(c) and (d). From artificial observations on the final scratch surface morphologies (figures 12(c)) and the middle scratch surface (figure 12(d)), the tendency of scratch surface quality and crack density can be obviously concluded that a coarser surface and more crack density occur under a larger normal force (namely larger scratch depth) qualitatively. Moreover, cracks and fractures in SiC particles are induced by the energy caused by the scratch process as soon as SiC critical fracture strength is exceeded. After fractures in SiC occurs, most of SiC fragments are removed as debris, but other occasions also happen. Marker I in figure 12(c) illustrates an occasion that a few SiC fragments that could not be discharge in time are pushed ahead by the grit and pressed again to the matrix; Marker II: a hole with residual SiC fragments; Marker III: disrupted scratch surface with pulverized SiC fragments scattering in the Al matrix; Marker IV: SiC particles.

**Figure 12.** SEM images of scratch groove for SiCp/5083Al with increasing normal force: (a) the overall scratch groove, (b) magnified view of the red region on the initial scratch surface, (c) magnified view of the red region on the final scratch surface, (d) magnified view of the blue region on the middle scratch surface, (e) magnified view of the blue region in (d), and (f) magnified view of the red region in (d). Marker I: a tiny groove lefted by a SiC fragment which are pushed ahead by the grit and pressed again to the matrix; Marker II: a hole with residual SiC fragments; Marker III: disrupted scratch surface with pulverized SiC fragments scattering in the Al matrix; Marker IV: SiC particles.
high thermo-mechanical stresses cause re-embedding of these SiC fragments into the Al matrix. Marker II in figure 12(e) depicts another occasion that pullout of the SiC fragments on the upper side and reservation of the SiC fragments underneath them lead to a hole with residual SiC fragments. Marker III in figure 12(e) shows the third occasion that disrupted scratch surface with pulverized SiC fragments scattering in the Al matrix occurs, which indicates that a large normal force (namely a large scratch depth) generates enough energy that pulverizes SiC particles and then further impresses these debris into the Al matrix, during the process the ductile Al between the debris is squeezed out because of its lower strength.

In addition to the above surface phenomena, particle-matrix interfacial debonding and lateral cracks on the Al matrix are especially worth noting, as shown in figure 12(f) where red dots are markers of SiC particles. A comparatively larger normal force (scratch depth) causes larger movement and deflection of SiC particles around within the Al matrix as well as more intense plastic deformation of the Al matrix, and significant differences in hardness and elastic modulus between SiC and 5083Al result in a fact that movement and of SiC particles could not accommodate with palstic deformation of the Al matrix as soon as the critical normal force (scratch depth) was exceeded for a certain SiC particle, the mechanical mismatch induces particle-matrix interfacial debonding to release the stress applied by the grit. As the normal force (scratch depth) increases, these particle-matrix interfacial debondings propagate and intersect with each other, which could lead to cracks (tear) in Al matrix, eventually large-scale lateral cracks on the Al matrix surface appear. According to observations from figures 12(c) and (d), lateral crack on the Al matrix surface is one of predominant surface defects.

It should be noted that the critical normal force (scratch depth) at which the above surface phenomena first appear varies highly depending on size and shape of the grit as well as the specimen material properties, such as matrix material, reinforced particle material, size and volume fraction of reinforced particles and processing technique. In the scope of this work where size and shape of the grit as well as the specimen material are specified in sections 2.1 and 2.2, the surface phenomena such as cracks and fractures in SiC particles, a tiny groove and a hole with residual SiC fragments first occur when the normal force is over 7 N, the surface phenomena of disrupted scratch surface with pulverized SiC fragments and particle-matrix interfacial debonding first appear when the normal force is over 9 N, the surface phenomenon of lateral cracks on the scratch surface first occurs when the normal force is over 13 N.

3.4. Explanatory models of the material removal mechanisms leading to scratch surface phenomena

To summarize description and discussion in section 3.3 where surface defects on SEM images are so numerous and messy that observations on typical surface defects is not convenient, brief and clear explanatory models are used to illustrate the surface phenomena.

Figure 13(a) shows the explanatory model for brittle material removal mechanism in a single scratch. In the subsurface stratum, there are plastic core and plastic zone below the contact site between the grit and workpiece, and close to the elastic-plastic boundary the median crack and lateral crack initiate, but the lateral crack propagates on a plane approximately parallelly to the scratch workpiece surface while the median crack spreads out perpendicularly to the scratch workpiece surface. On the scratch surface, the extended radial cracks distribute on both sides of the scratch groove in an angle ranging from 30° to 45° to the scratch direction, and larger peelings of material attributing to rapid intersection of radial cracks and lateral cracks with rapid increasing of the normal force (scratch depth) occur.

Figure 13(b) shows the explanatory model for ductile material removal mechanism in a single scratch. Similar to the brittle material removal, plastic core and plastic zone also exist below the contact site between the grit and workpiece, but there are no cracks. Smooth pile-up and scratch surface indicate that ductile material removal mechanism consists of ploughing and ductile cutting.

Figure 14 shows the explanatory model of material removal mechanisms leading to scratch surface phenomena for SiCp/Al at different scratch stages with increasing scratch depth. At a sufficiently small scratch depth shown in figure 14(a), possibly ductile removal mode of SiC particles as well as Al matrix is achieved, which can be verified by the smooth scratch surface and pile-ups, but deformation mismatch of hard SiC particles and ductile Al matrix leads to pressed-out SiC particles at the edges of the scratch groove.

As shown in figure 14(b), increasing scratch depth induces widespread particle-particle collision and rise of thermos-mechanical load which lead to cracks and brittle fracture in SiC particles and particle-matrix interfacial debonding because of deformation mismatch of hard SiC particle and ductile Al matrix. After brittle fracture of SiC particles, a hole with residual SiC fragments possibly forms because of removal of some SiC fragments and reservation of the others, besides, some SiC fragments beneath the grit leaves a tiny groove on the scratch surface, and eventually re-embedded into the Al matrix.

As shown in figure 14(c), with further increasing scratch depth, large-scale lateral cracks on the Al matrix surface forms because particle-matrix interfacial debondings propagate and intersect with each other. Rather, extremely high compressive stress could pulverize a SiC particle and instantaneously re-impress these SiC debris...
4. Conclusions

Experimented by single scratch tests with increasing normal force, this work clearly investigates and compares material removal behaviors of 50 vol% SiCp/5083Al, bulk SiC and bulk 5083Al. Scratch mechanical properties including scratch force, friction coefficient and AE signal, as well as cross-sectional profile creation including residual scratch depth and material removal ratio are introduced as good measures of material removal behaviors and material cutting efficiency at macroscale and mesoscope. Moreover, surface morphology of scratch grooves with help of SEM micrographs and explanatory models of material removal mechanism leading to scratch surface phenomena are used to understand material removal evolution at microscale. Based on the above results, the major conclusions can be drawn as follows.

(1) Considering the scratch mechanical properties including scratch force, friction coefficient and AE signal, the material removal behaviors of SiCp/5083Al are similar to that for 5083Al, but different from that for SiC at macroscale and mesoscope. Furthermore, higher hardness and smaller cross-sectional area of SiCp/5083Al attributing to presence of reinforced particles SiC lead to lower magnitudes and rates of the tangential scratch force and friction coefficient with severer fluctuations for SiCp/5083Al compared to 5083Al. On the other side, ductile matrix 5083Al improves plasticity and scratch characteristics of reinforced particles SiC via holding effect at macroscale and mesoscope, which can be identified by very low AE signal for SiCp/5083Al similar to that for 5083Al. As expected, influence of the normal force (scratch depth) on the scratch mechanical properties for SiCp/5083Al, 5083Al and SiC is significant, namely the tangential scratch force and friction coefficient for these three materials all increase with increasing normal force (scratch depth). Among these three materials under the same scratch condition, 5083Al exhibits the highest magnitudes and rates of the tangential scratch force and friction coefficient, while SiC shows the lowest ones until large brittle peelings of materials lead to rapid increase and severe fluctuations of the scratch mechanical properties.

(2) From the point of the cross-sectional profile creation characteristics including residual scratch depth and material removal ratio, the material removal behaviors for SiCp/5083Al are similar to that for 5083Al in ductile removal mode at macroscale and mesoscope, but different from that for SiC. Rather, presence of SiC particles results in lower magnitude of residual scratch depth and larger magnitude of material removal into the Al matrix as soon as a material-specific limit of compressive stress is exceeded, which also causes deteriorated deformation of Al matrix surrounded by these debris, accordingly, a disrupted surface with pulverized SiC fragments appears.
ratio with severer fluctuations for SiCp/5083Al compared to 5083Al. The material removal ratio variations reveal a fact that the material removal mechanisms are in the ductile material removal mode consisting of ploughing and cutting for SiCp/5083Al and 5083Al at macroscale and mesoscope, predominately brittle material mode for SiC, respectively. As the normal force (scratch depth) increases, the residual scratch depths for these three materials all increase, but their magnitudes and curves are different. On the other hand, with increasing normal force (scratch depth), materials removal ratios for SiCp/5083Al and 5083Al decrease with a similar trend, but conversely that for SiC increases.

(3) At microscale, surface morphology of scratch grooves with help of SEM micrographs and explanatory model of material removal mechanism leading to scratch surface phenomena illustrate that material removal behaviors for SiCp/5083Al are essentially different from typical ductile removal mode for 5083Al, also different from typical brittle removal mode for SiC. The material removal behaviors of SiCp/5083Al form a complicated process, including two-body friction between the grit and a particle SiC or between the grit and matrix Al, as well as three-body friction involving the grit, SiC fragments and matrix Al. The material removal behaviors for SiCp/5083Al as two-phase composite are the coupling results of brittle or ductile removal of reinforced particles SiC and ductile removal of matrix Al, where their removal behaviors influence each other, for instance, particles SiC cause surface tear and lateral cracks of matrix Al, in turn, matrix Al holds particles SiC to improve equivalently their plasticity and then increase the possibility of ductile removal for particles SiC.
(4) As for SiCp/5083Al, removal behaviors of particles SiC which is predominantly influenced by the normal force (scratch force) plays a crucial role in the whole SiCp/5083Al removal process and scratch surface quality, according to SEM micrographs of scratch surface and explanatory model of the material removal mechanism at macroscale. Predominantly ductile removal of particles SiC results in a comparatively smooth scratch surface, conversely, predominantly brittle removal of particles SiC lead to a deteriorative scratch surface characterized by cracks and fracture in particles SiC, particle-matrix interfacial debonding, holes with residual SiC fragments, SiC fragments re-embedded into matrix leaving a tinny groove on the scratch surface, large-scale lateral cracks on Al matrix surface and disrupted surface with pulverized SiC fragments.

(5) Overall, at macroscale and mesoscale the material removal behaviors of SiCp/5083Al are similar to that for 5083Al, but different from that for SiC, at microscale the material removal behaviors for SiCp/5083Al as a two-phase material are essentially different from that for 5083Al and SiC. The significant dominance of the normal force (scratch depth) in material removal behaviors for SiCp/5083Al, SiC and 5083Al is highlighted. Concerning SiCp/5083Al, it is possible that sufficiently low normal force (namely scratch depth) could achieve ductile material removal of the matrix Al as well as reinforced particles SiC, which is supported by the SEM micrographs of the scratch surface when the normal force is less than 7 N in the scope of this work. Therefore, it is suggested to select a sufficiently low scratch depth to achieve ductile removal mode of the two-phase material SiCp/Al under a certain grinding condition and then generate a good scratch surface quality.

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ORCID iDs

Xu Zhao @ https://orcid.org/0000-0003-3018-2493

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