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Abstract
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Scratch with double-tip tool: crack behavior during simultaneous double scratch on BK7 glass

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Abstract: Over the past decade, successive double-scratch tests have been extensively performed to study the grinding mechanism of brittle materials. However, the grits sometimes interact with the surface simultaneously. In this study, double tips with a tip separation of 0.6–1.8 µm are fabricated by focused ion beam. Subsequently, double-scratch tests on BK7 optical glass are conducted using the double-tip scratch tool with a scratch depth of 200–600 nm. The typical crack system and its evolution mechanism for double-tip scratch are discovered, before being explained using an analytical stress model. The ductile–brittle transition and the material-removal mechanism are discussed. An influential radius for the interference between cracks and the stress field in the double scratch is obtained, which can serve as a reference for the design of textured grinding wheels. Subsequently, the advantages and disadvantages of double-tip scratches are discussed considering different applications, such as microstructure fabrication and grinding.

Keywords: double-tip tool; focused ion beam; simultaneous double scratch; BK7 optical glass; crack behaviors

1 Introduction

Single scratch test has been extensively conducted to gain a fundamental understanding of the material removal mechanism of brittle material. However, there is still interaction between grits which
the single scratch test is not capable of revealing[1,2]. In grinding, two types of grit–workpiece scratching exist: successive and simultaneous, which have been studied through the successive double-scratch test and multitip scratch test, respectively.

The first type of interaction is successive grit–workpiece interactions, where two grits interact with the workpiece sequentially. Because only one indenter/tip is required in such tests, as shown in Fig. 1(a), this type of test has been studied extensively in recent years. Successive double scratch was first used to investigate the effect of grit separation on the material-removal mechanism in brittle mode during grinding[3,4]. On alumina ceramic, BK7 optical glass, and glass–ceramic, it has been discovered that the material removal rate depends significantly on the separation distance between scratches, and that a critical separation distance exists to obtain the maximum material removal rate. Subsequently, using different sectioning methods, the intersection of different types of cracks and the henceforth promoted material removal process is revealed [5,6]. Furthermore, a few studies have focused on the penetration depth and plastic recovery during double-scratch tests [7] as well as the effect of scratch sequence in triple scratches on the stress distribution and chipping behaviors [8]. Apart from the experimental approach, researchers have used simulations to explain the interaction between two scratches, including finite element method and the smooth particle hydrodynamic method [9–11]. However, during a double scratch, the effect of the residual stress remaining after the first scratch on the behavior of the second scratch, especially crack behaviors, is yet to be elucidated. Recently, a study on successive double scratches revealed unique crack behaviors under a critical load for median crack initiation, which included a premature lateral crack initiation and the suppression of median crack due to the effect of residual stress [12]. These special crack behaviors are evidence of the effect of residual stress on the initial crack behaviors under the critical condition for ductile–brittle transitions.

The second type of interaction is the simultaneous grit–workpiece interaction, typically investigated through comultitip scratch tests. Studies regarding multitip scratch tests are few because of the difficulty in fabricating multitip tools. As shown in Fig. 1(b), a simultaneous double-scratch test involves an indenter with two tips that require extremely high precision accuracy, which is challenging to fabricate through machining. One preferred method for multitip tools is focused ion beam (FIB) milling. Over the past decade, multitips measuring ten microns [13–15] to hundreds of nanometers [16–18] have been fabricated using FIB, yielding significantly improved shape accuracy and some
identical tips in some cases [17]. In previous studies, the shape transferability as well as thermal effects and plastic behaviors, such as pile-ups, have been thoroughly investigated; however, they were not conducted on brittle materials, such as glass or ceramics. Meanwhile, unlike successive double scratches, the effect of residual stress is not present during simultaneous double scratches; however, the overlapping of the scratch stress field can result in unique crack behaviors that have not yet been revealed. Therefore, it is crucial to apply simultaneous double scratches on brittle materials and investigate the mechanism behind the crack behaviors.

In this study, the crack behaviors during simultaneous double-scratch testing were investigated using a scratch tool with two tips fabricated via FIB milling. The separation between two tips was from 0.6 to 1.8 μm. To explain both the ductile and brittle behaviors in the simultaneous double-scratch test, an analytical model for stress analysis was performed. The results of the tests were then compared with those of our previous study, which focused on successive double scratches. Finally, the influential radius of stress, as well as the ductile and crack behaviors in double scratches, are discussed to provide references for future similar studies, including grinding mechanisms and submicron structure machining.

![Fig.1 Schematics for successive double scratches and multitip scratches.](image)

### 2 Experimental methodology and analytical model for stress

#### 2.1 Double-tip tool fabrication

The indenter used in the experiment was originally a diamond cube-corner tip for nanoindentation tests. As shown in Fig. 2 (a), the cube-corner tip had an apex angle of 101.3° and a rake angle of -54.7° when the scratch was applied in the edge-forward direction. Prior to the fabrication of the double tip,
the tip was used to apply a few single scratches to obtain the basic scratch morphology on BK7 glass.

Figs. 2 (b) and (c) show the scheme for the fabrication of the double tip. The double tip was machined on a Tescan LYRA 3 FIB field emission SEM using a 10-KeV and 5-pA FIB. The incidence direction of the FIB was perpendicular to the vertical plane, as shown in Fig. 2 (c), thereby ensuring the same apex angle of all tips. Consequently, the rake surface of the double tip was protected from the etching by the FIB while the apex angle of each tip remained the same. These were both important aspects that could significantly affect the crack behaviors in nanoscratching [19]. To apply a double-tip scratch with different separation distances, the tip was first machined with a tip separation of \( D_m \), as shown in Fig. 2. To ensure that the result would not be significantly affected by the shape accuracy, the double tip was machined again with the same separation; subsequently, it was used to conduct the test again. The experimental result with a more uniform scratch morphology is presented herein. After performing FIB machining twice and conducting two tests for the first separation distance value, the next separation distance \( D_m' \) was tested. The cycle was repeated until all experiments using the selected separation distances had been conducted. In this study, the tool wear of the rake surface was a concern; however, under each FIB milling, the old worn area was machined, whereas the new area of the flank surface became the new tool flank.

However, it is noteworthy that the tip edge length \( l_t \) shown in Fig. 2 (c), which is the length of the edge formed during FIB machining, increased as the tip was further machined with a larger tip separation. Even though the front wear in the test and the etching of flank surface by FIB can reduce the actual edge length \( l_a \), we conducted all tests with the same scratch depth instead of the same scratch load, as the load might increase when \( l_a \) is increased.
Fig.1. (a) Geometry of a cube-corner tip; (b) front view of double tip and the FIB milling scheme; (c) side view of double tip and FIB milling scheme. The vertical dash-dotted line is the center axis of the indenter. The front view was obtained from a direction that was also the FIB incident direction and the scratch direction. It is also known as edge-forward, as an edge leads in the scratch process, while the face forward direction pushes the material by the surface when scratching. The apex angle of the indenter is the angle of the tip projection on the front view, which was 101.3°. The rake angle, i.e., the angle between the edge and the center axis, was 54.7°.

2.2 Experimental setup

As explained above, the separation distances between the two tips were 0.6, 0.8, 1.0, 1.2, 1.4, and 1.8 µm, respectively. All scratch tests were conducted on an Agilent G200 Nanoindenter and the scratch depths were 200, 300, 400, 500, and 600 nm, respectively. Therefore, a transformation from ductile to brittle mode can be expected as the ductile–brittle transition critical depth for BK7 glass is approximately 300 nm[20,21]. Owing to the change in the tip edge length, the load of a given scratch depth for double tips of different separations differs. Therefore, the scratch load for a given depth was first obtained by conducting a ramp-load test with increasing load from 0 to 20 mN. Subsequently, in constant depth scratch tests, the obtained scratch load was maintained during the scratch process, whereas the scratch depth was monitored in real time to ensure that the actual scratch depth was correct. All scratches were 100 µm long and were applied at a speed of 2 µm/s. Prior to the test, all BK7 glass
specimens were polished and then cleaned using ethanol in an ultrasonic cleaner for 15 min.

The scratched surface was then covered with gold and inspected through SEM to capture the surface morphology of all scratches. Multiple spots on the scratch grooves were selected to be milled via FIB on a Tescan LYRA 3 XMU FIB field emission SEM, where subsurface cracks were exposed and captured through SEM. The scheme for the FIB cross-sectioning is shown in Fig. 3; it involves two steps—rough milling and finishing. During the FIB cross-sectioning process of the scratch grooves on the BK7 glass, a 10-KeV, 3-nA FIB was used, and the current for the finishing beam was 500 pA.

![Diagram](image_url)

Fig. 1. Scheme for FIB cross sectioning that exposes the subsurface cracks immediately under the scratch groove. During the process, a ramp was created to observe the cross section through SEM. The cross section was first milled with a 10 KeV, 3 nA FIB; subsequently, a fine finishing was conducted with a 500-pA beam to clear splattered materials on the cross section.

2.3 Analytical model for stress

The analytical model for stress used in this study was based on Jing’s model [22], which is a superposition of the Boussinesq, Cerruti, and Blister fields. The overall scratch stress field can be expressed as

$$
\sigma_{ij} = \sigma_{Bij} + \sigma_{Cij} + \sigma_{Bij},
$$

where \(\sigma_{Bij}\), \(\sigma_{Cij}\), and \(\sigma_{Bij}\) are the Boussinesq, Cerruti, and sliding blister fields, respectively; \(\sigma_{ij}\) is the overall friction coefficient; \(k_{ij}\) the strength of the sliding blister field. Subscripts \(i\) and \(j\) are the stress components in the \(x\), \(y\), and \(z\) directions.

The material properties of BK7 used in this model are listed in Tab. 1. As for the expression of all fields, please refer to Appendix A.

Tab. 1. Material Properties of BK7 Glass
### Table 1

<table>
<thead>
<tr>
<th>Young’s Modulus $E$ (GPa)</th>
<th>Poisson’s ratio $\nu$</th>
<th>Vickers hardness $H$ (GPa)</th>
<th>Volume contraction rate $f$[20]</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>0.203</td>
<td>7.6</td>
<td>0.106</td>
</tr>
</tbody>
</table>

3 Results and discussion

3.1 Geometry of the double tip fabricated by FIB milling

The geometry of the double tip fabricated by FIB milling demonstrated promising shape accuracy. As shown in Fig. 3 and Tab. 2, the separation between two tips was well controlled with only a small error. Furthermore, the error for the apex angle did not exceed 10°. As reported from a previous study [5], the effect of the apex angle can change the material-removal mode and the crack behaviors during scratching. However, in this study, the difference in the apex angle was smaller than 10°; therefore, it was assumed that the crack behavior mode remained the same.

![Diagram of double tip geometry](image)

Fig. 1. Double tips milled by FIB with tip separations of 0.6, 0.8, 1.0, 1.2, 1.4, and 1.6 µm. The magnification
for the SEM images were 100k, 60k, 60k, 40k, 30k, and 30k, respectively, which were selected to depict the shape of the double tip at a relatively similar size on screen more effectively. Gold plating was used for both SEM and FIB milling, as diamond is not a conductive material.

Tab. 2 Parameters of all double tips

<table>
<thead>
<tr>
<th>Designed Separation distance $D_s$ (µm)</th>
<th>Measured separation distance $D_m$ (µm)</th>
<th>Tip height difference $h_2 - h_1$ (µm)</th>
<th>1st tip radius $r_1$ (µm)</th>
<th>2nd tip radius $r_2$ (µm)</th>
<th>1st tip apex angle $\alpha_1$ (°)</th>
<th>2nd tip apex angle $\alpha_2$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.622</td>
<td>0.049</td>
<td>0.12</td>
<td>0.08</td>
<td>102.41</td>
<td>96.45</td>
</tr>
<tr>
<td>0.8</td>
<td>0.799</td>
<td>0.061</td>
<td>0.09</td>
<td>0.07</td>
<td>99.508</td>
<td>107.061</td>
</tr>
<tr>
<td>1</td>
<td>0.99</td>
<td>-0.052</td>
<td>0.11</td>
<td>0.09</td>
<td>96.892</td>
<td>110.438</td>
</tr>
<tr>
<td>1.2</td>
<td>1.171</td>
<td>0.068</td>
<td>0.05</td>
<td>0.08</td>
<td>109.061</td>
<td>101.31</td>
</tr>
<tr>
<td>1.4</td>
<td>1.454</td>
<td>0.012</td>
<td>0.1</td>
<td>0.08</td>
<td>107.754</td>
<td>102.671</td>
</tr>
<tr>
<td>1.6</td>
<td>1.575</td>
<td>-0.055</td>
<td>0.13</td>
<td>0.14</td>
<td>106.26</td>
<td>107.16</td>
</tr>
</tbody>
</table>

Two other factors that significantly affect the scratch behavior heavily were the tip height and tip radius. As shown in Tab. 2, the difference in the tip height was less than 0.07 µm, whereas the difference in the tip radius varied from 0.07 to 0.14 µm. It is noteworthy that the tip wear was more severe when the tip was sharper and higher. Therefore, the differences in the two abovementioned parameters will decrease as the tips wear out gradually worn after a few scratches.

Occasionally, the symmetry of the two tips affected the scratch results significantly. As shown in Fig. 5(a), the width of the left scratch was more than twice the width of the right one. Therefore, all scratches applied using this tool were excluded. The tip corresponding to this scratch is shown in Fig. 5(b). Notably, even though the tip length and tip radius were similar, a part of the second tip was heavily etched during FIB milling. During the scratch test, the damaged area was worn quickly; therefore, the subsequent scratches became asymmetric.
In conclusion, the shape accuracy of the double tip was good when it was fabricated in the scale near 1 μm; however, the quality of the tip can be significantly affected by the ion beam condition. Therefore, the FIB condition should be closely monitored and the milling time for each pass minimized.

3.2 Typical crack system in double-tip scratch

During the inspection of subsurface cracks of all double-tip scratches with different tip separations and scratch depths, a typical crack system that was distinct from the single crack system appeared when the tip separation was small and the scratch depth passed the critical value for ductile–brittle transitions (DBTs). As the tip separation increased, the typical crack system slowly transformed into two independent single scratch crack systems. Fig. 6(a) shows the cross-section image of subsurface cracks in the double-tip scratch at a tip separation of 0.6 μm and depth of 300 nm. It was discovered that the median crack no longer initiated at the bottom of each scratch; instead, it initiated at the ridge between two scratches. Hence, only one median crack, termed the middle median crack (MMC) herein, was initiated in the middle zone. Furthermore, a special lateral crack traversed the middle zone. The traversed lateral crack (TLC) connects the two bottoms of the double-scratch grooves. In addition, a lateral crack appeared on the outskirts of the double-scratch grooves. Therefore, a typical crack system of simultaneous double scratches comprised one median crack, a traversed lateral crack, and two lateral
cracks, as depicted in Fig. 6 (b).

![Diagram](image)

Fig. 1. (a) SEM image and (b) sketch of the typical crack system in a double-tip scratch when the tip separation was 0.6 μm and the depth was 300 nm. The crack system comprised a middle median crack, a traversed lateral crack, and possible lateral cracks on the outskirts.

The appearance of the MMC and the TLC can be explained through an analytical stress-field analysis. As shown in Fig. 7, the median crack initiated under a tensile stress immediately below the scratch in the single scratch. However, as shown in Fig. 7 (b), in the double-tip scratch, the middle zone between the two scratches became the initiation point of the median crack because the tensile stress $\sigma_{yy}$ at this point was the largest owing to the overlapping of tensile stress from the two scratches. Therefore, the median crack initiated in the middle zone instead of under each scratch. As for the TLC in the double-tip scratch, as shown in Figs. 7 (c–d), the tensile zone below each scratch in the distributions of $\sigma_{yy}$ and $\sigma_{zz}$ were connected and strengthened, which provided an ideal condition for the initiation and propagation of the traversed lateral crack.
3.3 Evolution of crack behaviors occurring in double-tip scratch

As analyzed previously, the typical crack system during a simultaneous double scratch comprises an MMC, a TLC, and two LCs. However, the crack behaviors change as the separation distance between two tips and the scratch depth increase.

As shown in Fig. 8 (a), the scratch is crack-free when the scratch depths were 200 and 300 nm. However, when the scratch depth increased from 300 to 400 nm, MMCs and TLCs started to appear when the separation was 0.8 and 1.0 µm, whereas the scratch was still ductile when the separation distance was equal to or larger than 1.2 µm. As shown in Figs. 9 (a) and (b), in front of the double-tip where a median crack is typically initiated, the strengthened tensile middle zone can only be observed when the separation distance was 0.8 µm when the scratch depth was 400 nm. As the separation
distance increased, the tensile region below each scratch started to separate; therefore, the strengthened spot in the middle zone vanished when $D$ increased to 1.0 μm. Without the strengthened effect of stress from the opposite scratch, the maximum value of stress component $\sigma_{y y}$ decreased. Consequently, no median crack was initiated when the separation distance reached 1.0 μm for a scratch depth of 400 nm.

Owing to the strengthened stress effect in the simultaneous double scratch, the DBT critical depth for scratches with different separation distances differed. The DBT critical depth increased from 400 to 500 nm when the tip separation reached 1.2 μm, as marked by the red line in the table in Fig. 8.

As the scratch depth reached 500 nm, all scratch groups exhibited brittle behaviors. However, it is noteworthy that the MMCs became independent MCs when the separation distance exceeded 1.2 μm; this is shown in Fig. 8 (c). As shown in Fig. 9 (c–e), the strengthened stress region of $\sigma_{y y}$ vanished as the separation distance increased from 0.8 to 1.2 μm. However, unlike the situation when the scratch depth was 400 nm, the tensile stress of $\sigma_{y y}$ under each scratch was sufficiently large for the median crack to initiate independently. Consequently, the median crack no longer appeared in the middle zone but under each scratch.

LCs appeared on the outskirts in all scratch groups despite their separation distance. Even though LCs propagate horizontally similar to TLCs, the effect of stress from the opposite scratch is not as strong as that of TLCs; therefore, the initiation depth for LCs is more uniform. Meanwhile, the initiation of TLCs appears in different scratch depths at different separation distances. The initiation line for TLCs is shown in the table in Fig. 8. TLCs were initiated when the scratch depth reached 400 nm in the 0.8- and 1.0-μm separation groups. Furthermore, TLCs were delayed and only appeared when the scratch depth reached 500 nm in the 1.2- and 1.4-μm separation groups, similar to the MMCs. However, the initiation of TLCs was postponed in the 1.6-μm separation group, as shown in Fig. 8 (b). In the 1.6 μm group, only MCs and outskirt LCs appeared when the middle zone was free of TLCs.

As shown in Fig. 10, the stress components responsible for crack initiation $\sigma_{y y}$ and further propagation $\sigma_{zz}$ were both strengthened when the separation was as small as 0.8 μm. However, the strengthening effect disappeared as the tensile zone below each scratch gradually became more independent. The change in stress distribution here gradually reduced the possibility of the initiation of TLCs, whereas the initiation of LCs on the outskirt remained unchanged. In particular, as shown in Fig. 10 (e), the
compressive zone of stress component $\sigma_{zz}$ overlapped and strengthened in the middle zone when the separation was 1.6 $\mu$m, which eliminated the possibility for any type of horizontal crack to propagate.
Fig. 1. Subsurface SEM images of the double-tip scratch. Three crack evolutions due to depth increment and separation increment are marked in three different colors, with the subsurface images shown in (a), (b), and (c). In particular, “0” in the table means no cracks is observed, and “-” represents no test conducted under this condition. (a) The surface and subsurface SEM images of the double scratch with a 400 and 500 nm scratch depth and a tip separation of 0.8 µm, showing the appearance of LCs; (b) The surface and subsurface SEM images of the double scratch with a 500 nm scratch depth as the scratch depth increased from 1.4 to 1.6 µm, where the MLC started to disappear; (c) The surface and subsurface SEM images of the double scratch with a 500 nm scratch depth as the scratch depth increased from 1.2 to 1.6 µm, showing the disappearance of MMCs and emergence of MCs under each scratch. The table at the bottom is for all subsurface crack behaviors observed in our experiment under different scratch depths and tip separations.

Fig. 1. Distribution of stress component $\sigma_{yy}$ ahead of the double-tip scratch tool: (a) $D_s = 0.6$ µm, $d = 400$ nm; (b) $D_s = 1.0$ µm, $d = 400$ nm; (c) $D_s = 0.8$ µm, $d = 500$ nm; (d) $D_s = 1.2$ µm, $d = 500$ nm; (e) $D_s = 1.6$ µm, $d = 500$ nm. The unit for both axes is µm. From (a) to (b), the strengthened tensile zone disappeared, and the tensile stress under each scratch was less than 1; therefore, the MMCs disappeared but no independent cracks
appeared under each scratch; From (c) to (e), the strengthened tensile zone disappeared, but the tensile stress under each scratch was larger than 1; therefore, independent median cracks were initiated.

![Stress field behind the double-tip scratch](image)

Stress field behind the double-tip scratch

\[d = 500 \text{ nm}\]

Two separated tensile stress regions appeared under each scratch in the distribution of \(\sigma_{yy}\), which overlapped and strengthened when \(D_s\) was 0.8 µm. From (a) to (b), when the distance increased to 1.4 µm, the tensile stress regions started to separate. From (c) to (d), the stress distribution of \(\sigma_{zz}\) started to separate and became independent during the process, lowering the possibility of both the initiation and propagation of lateral cracks in the middle zone.

3.4 Material removal mechanism of double-tip scratch

The material-removal mechanism during double-tip scratching changes with the evolution of the
crack behaviors. As shown in Fig. 11, two major surface fracture modes appear in the double-tip scratch: the fractured middle zone (FMZ) and lateral crack chipping (LCC). Their initiation critical lines are marked on the table, which indicate significantly different initiation mechanisms. LCC is less affected by the separation distance of the tips, as it is only contributed to by LCs on the outskirts, which remain unaffected by any other tip.

Meanwhile, the FMZ exhibits a more complex behavior. When the tip separation was smaller than 1.2 µm, the FMZ appeared owing to both MMCs and TLCs. As shown in the subsurface SEM images, the MMC in the middle zone and the TLC that traversed under the middle zone separated the ridge in the middle into multiple pieces. As shown in Figs. 11(c2) and (d2), the material in the middle zone was removed in a manner similar to a small chip being peeled off from the surface. In single-scratch tests, the material can only be removed by the LCs, while the MCs exert almost no effect on the material-removal process. However, in the middle zone, by intersecting with the TLCs and cutting off the material in the middle, the MCs rendered it considerably easier for chipping to form and be removed.

The FMZ appeared when the tip separation was larger than 1.2 µm. As the median crack became independent, the middle zone was no longer cut off by MCs; therefore, the FMZ was only contributed by TLCs. Such an FMZ has almost no chippings but only small cracks that can be observed from the surface. The stress model shows that the effect of stress weakened the middle zone with such a big tip separation. Therefore, fewer cracks appeared. Meanwhile, with the increase in the tip separation, the material in the middle zone increased as well; therefore, the strength of the ridge in the middle was higher. Because of fewer cracks and the middle zone being bulkier, no obvious middle-zone chippings were formed.
Fig. 10. Surface SEM image of the double-tip scratch. The table shows all the surface crack behaviors that induce material removal under the effects of the scratch depth and tip separation. In particular, “0” in the table means no cracks is observed and “-” represents no test conducted under this condition. (a), (b) Completely ductile scratch morphology when (a) $D_s = 0.6 \, \mu m$, $h = 300 \, nm$ and (b) $D_s = 1.2 \, \mu m$, $h = 400 \, nm$; (c) surface morphology of FMZ with MMC when $D_s = 0.8 \, \mu m$ and $h = 400 \, nm$; (d) surface morphology of scratch with both FMZ and LCC when $D_s = 1.2 \, \mu m$ and $h = 600 \, nm$; (e) surface morphology of scratch with only LCC when $D_s = 1.4 \, \mu m$ and $h = 500 \, nm$. 

<table>
<thead>
<tr>
<th>$D_s$</th>
<th>0.6 $\mu m$</th>
<th>0.8 $\mu m$</th>
<th>1.0 $\mu m$</th>
<th>1.2 $\mu m$</th>
<th>1.4 $\mu m$</th>
<th>1.6 $\mu m$</th>
</tr>
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<tbody>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>300 nm</td>
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<tr>
<td>400 nm</td>
<td>0</td>
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</tr>
<tr>
<td>500 nm</td>
<td>-</td>
<td>FMZ</td>
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<td>600 nm</td>
<td>-</td>
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</tbody>
</table>

- : no test under this condition
0: no crack observed
FMZ: fractured middle zone
LCC: lateral crack chipping
3.5 Scratch influential radius

Previously, a successive double scratch focusing on the initial crack behavior was applied [12]. In the successive double scratch, the crack system under the first scratch was not affected by any factor as the scratch was applied on a clean and intact surface. However, the second scratch was applied with both the groove and residual stress of the first scratch present. In the previous study, we demonstrated how a crack system under the second scratch was affected by the residual stress of the first scratch. As shown in Fig. 12, the second crack system underwent two stages before becoming independent, implying that it was no longer affected by the first scratch.

![Unique crack behavior in successive double scratch under critical load of media crack initiation.](image)

However, in the double-tip scratch in this study, no effect of preexisting residual stress between two scratches was observed, because the two scratches were applied simultaneously. However, two separated crack systems, which had at least a median crack immediately under each scratch groove, did not appear until the tip separation reached 1.4 µm. The material appeared to treat the double tip as one tip when the tip separation was less than 1.4 µm. Hence, only one median crack appeared in the middle zone, which separated the ridge in the middle into two parts. When the tip separation exceeded 1.4 µm, the crack in the middle zone was suppressed under the effect of compressive stress from each scratch. However, the interaction between the scratch weakened as the separation exceeded 1.8 µm, which was similar to the critical value for the independent stage in the successive double scratch.

The aforementioned critical distance for the “independent stage” is a parameter that describes the influential radius of a scratch at the micrometer scale. In recent studies, the influential radius has been calculated based on different theories. For example, Luo et al.[17] considered the influential radius to be the radius of a plastically deformed zone, which is approximately eight times the scratch width.
according to the equation \( c^3 \frac{E}{3(1-v)} \), where \( c \) is the plastic deformation zone radius, \( a \) the scratch width, and \( Y \) the yield strength of the material. In Duan et al.’s study, the influential radius was considered as the distance where the effect of plastic damage no longer existed, which was approximately 150 \( \mu \)m for a 20 \( \mu \)m radius tip [23].

In this study, the influential radius focuses more on how the stress affects the crack behavior of the opposite scratch, instead of the plastic damage or crack intersection. The implementation of such a value can be considered as a reference for the design of textured grinding wheels, as the separation distance between grits has never been considered an important parameter. Fig. 13 shows the maximum principal stress of the 1st and 2nd scratches when two scratches are 2.0 \( \mu \)m away and the depth is 300 nm. As shown, the stress distribution of component \( \sigma_{yy} \) at the bottom of the scratch decreases rapidly as the distance increases because the stress is inversely proportional to the square of the distance. Here, the red line and the blue dotted line marks indicate where the stress component decreased below 1.0 and 0.5, respectively. When the distance reached 0.6 \( \mu \)m, the stress component was approximately 1.0, which signified the potential limit for crack initiation. The stress component decreased to 0.5 when the distance increased to almost 0.9 \( \mu \)m. This implies that the lowest point on the green line, which is the sum of the stress of the first scratch and the second scratch, will not reach 1.0 if the separation distance of two scratches is larger than 1.8 \( \mu \)m, causing the tensile stress zone under each scratch to be separated.

![Stress distribution of maximum principal stress at the depth of the scratch groove bottom when the](image)

Fig. 10. Stress distribution of maximum principal stress at the depth of the scratch groove bottom when the
separation distance is 2.0 µm and the depth is 300 nm. The stress curve of the 1st and 2nd scratches and their sum are shown. The vertical red and blue lines signify the locations from the scratch center, where the maximum principal stress decreases to 1.0 and 0.5, respectively.

Therefore, based on the result of the double scratch and the maximum principal stress distribution, the influential radius was approximately 2.0 µm for a scratching depth of 300–600 nm. Therefore, the grit separation should be set to at least more than 2.0 µm if the designer of a textured grinding wheel wishes to avoid the interference of stress.

3.6 Comparison with simultaneous double scratch

Micro- and nanomachining are new methods of fabricating microstructures. The scratch behavior discovered in this study can provide insights into the selection of processing parameters.

In the successive double scratch, the effect of feed rate is problematic for microstructure fabrication, as the ridge between two passes often collapse when the tip separation is small [24]. As shown in Fig. 14, when the tip separation distance was less than 1.0 µm, the ridge between two scratches always collapsed plastically toward the first scratch. A similar effect has also been reported in previous nanoscratch studies, in which the middle zone collapsed and some of the materials were splattered to cover the first scratch [24–26]. Another problem in fabricating structures using successive scratch is aligning, because the precise control of a feed requires an accurate movement in the nanometer scale [27].

Meanwhile, the structure shape accuracy was improved significantly when the double-tip tool was used. As shown in Fig. 14, inside the ductile zone, the ridge always maintained its shape even when the tip separation distance was as small as 0.6 µm. In recent years, both experiments of nanoscale double-tip scratch and its molecular dynamics simulations have indicated that the shape transferability was much better compared with that of a successive scratch [17]. Therefore, the results of this study and recent studies support that a simultaneous scratch is better for the fabrication of nanostructures.
In a previous study [12], we discussed how a premature LC and the suppression of median cracks is beneficial to the grinding process if it can be utilized in grinding with an ordered grinding wheel. However, in this study, it was discovered that, owing to the strengthened effect of stress in the middle zone, MMCs typically appeared in double-tip scratches, which separate the middle zone into two parts. Even though the strengthened effect of stress when the tip radius was smaller than 1.2 µm has been proven to be detrimental to the surface integrity because it promoted the initiation of MMCs and TLCs, it was observed that the DBT critical depth in the simultaneous double scratch was larger than that of the single-scratch test. Fig. 14 shows a direct comparison between the successive and simultaneous double scratches under the same separation distance and scratch depth. As shown, the latter was completely crack-free. However, it is noteworthy that it was extremely difficult to determine whether the phenomenon was due to the compressive stress under both tips or the differences in the tip geometry, as the shape of the tip in this study and that of the cube-corner tip were not exactly the same owing to the long tip edge. Therefore, we shall investigate the differences between successive and
simultaneous scratches in the future using a well-designed scratch tool that can minimize the effects of other factors.

4 Conclusions

Double-tip scratch tools with different tip separations were fabricated in this study using FIB milling. The double-tip scratch was subsequently inspected under SEM. Furthermore, the subsurface was exposed, whereas all the subsurface cracks were captured using FIBs. After analyzing the results of the subsurface and surface crack morphology, the following conclusions were drawn:

(1) The typical crack system for a double-tip scratch comprised an MMC propagating between two scratches owing to the overlapping of tensile stress in the middle zone, a TLC traversing under a middle zone because of the strengthening of tensile stress behind the scratch tool, and two normal LCs expanding outward.

(2) As the scratch depth increased, MCs and TLCs appeared together; subsequently, LCs began to appear. When the tip separation increased, the MMCs in the middle zone was replaced by two MCs under each scratch. The initiation of TLCs was postponed as the separation distance increased because the strengthening effect of stress weakened gradually. Consequently, the DBT critical value increased from 400 to 500 nm as the tip separation distance increased to 1.4 μm.

(3) The FMZ and LCCs contributed to the material removal process. The LCCs were primarily dependent on the scratch depth instead of the separation distance. Meanwhile, the FMZ was caused by the intersection of MMCs and TLCs when the separation distance was less than 1.2 μm.

(4) The crack behaviors indicated that the critical influential radius for the crack system below the scratch tip was approximately 2.0 μm; this was verified using the analytical stress model.

(5) When considering the shape transferability in structure fabrication, the double-tip scratch offered a better advantage compared with the successive scratch method.

Declaration of interests

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


[20] W. Gu, Z. Yao, Evaluation of surface cracking in micron and sub-micron scale scratch tests


