Abrasive micro-blasting to improve surface integrity of electrical discharge machined WC–Co composite

Jun Qu a ,∗, Albert J. Shih b , Ronald O. Scattergood c , Jie Luo b

a Metals and Ceramics Division, Oak Ridge National Laboratory, P.O. Box 2008, MS 6063, Oak Ridge, TN 37831-6063, USA
b Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA
c Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC 27695, USA

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Abstract

This study investigates the improvement of surface integrity of wire electrical discharge machined (EDM) WC–Co composite by abrasive micro-blasting. The thermally damaged recast layer generated by EDM has craters, cracks, and bubbles, which deteriorate the surface mechanical properties. The micro-blasting, using 6–12 and 4–20 μm size SiC abrasive, enables the removal of the recast layer and is suitable for micro mechanical components. The surface roughness of EDM rough cut WC–Co parts was improved significantly, with the average surface roughness (Ra) dropping down from 1.3 to 0.7 μm. Scanning electron microscope (SEM) was used to examine the evolution change of surface texture and subsurface cross-section of EDM WC–Co workpiece. The SEM micrographs showed that the recast layer was removed efficiently. After 5 s of micro-blasting, surface textures with ridge and cavity patterns were observed on fine and rough cut EDM surfaces, respectively. These surface textures could be correlated to the surface roughness measurement and crater formation in EDM spark erosion. A series of erosion wear experiment was conducted to quantify the weight reduction, calculate the erosion wear rate, and identify the wear mechanism.

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1. Introduction

Electrical discharge machining (EDM) is a thermoelectric process that erodes workpiece material by a series of discrete electrical sparks between the workpiece and electrode. Unlike traditional cutting and grinding processes which rely on a much harder tool or abrasive material to remove the softer work-material, the EDM process utilizes electrical sparks or thermal energy to erode the unwanted work-material and generate the desired shape. The hardness and strength of the work-materials are no longer the dominating factors that affect the tool wear and hinder the machining efficiency. This makes EDM particularly suitable for machining hard, difficult-to-machine materials, such as the metal–matrix composites (MMC). As shown in Fig. 1, the wire EDM process uses a traveling wire as the electrode to erode a groove in the workpiece. The close-up view of the gap and electrical sparks between the wire and workpiece is illustrated in Fig. 1(b). Mechanical properties of surface layers generated in this process are important to the part performance, particularly the fatigue and wear life.

Although EDM can machine precise, complex, and intricately MMC components [1–4], the undesired surface recast layer and sub-surface heat-affected zone (HA) are generated [5]. Fig. 2 shows SEM micrographs of the surfaces and subsurface cross-sections of a WC–Co sample machined under 14 and 2 μs pulse on-time and 28 μs spark cycle. Pulse on-time is defined as the duration of high voltage in the electrical spark cycle, which is an important EDM process parameter that affects the thicknesses of the recast layer and heat-affected zone [2]. Electrical sparks melt the work-material
and generate craters, bubbles, and cracks in the recast layer, marked as RL in Fig. 2. A sub-surface heat-affected zone has essentially no porosity and exists between the recast layer and the bulk material. As shown in Fig. 2(a), the longer (14 μs) pulse on-time creates thicker recast layer and heat-affected zone.

The surface integrity, including the roughness, size of craters, and thicknesses of the recast layer and heat-affected zone, of a wire EDMed WC–Co surface has been investigated [2]. Nanoindentation, EDS X-ray, and X-ray diffraction have been applied to study the mechanical properties (hardness and modulus of elasticity) and material compositions of the EDM WC–Co surface layers [6]. Nanoindentation and SEM results show the heat-affected zone has more compact microstructure and higher hardness and modulus of elasticity than that of the bulk material [6]. The recast layer with craters, cracks, and bubbles deteriorates the surface properties and reduced the wear and fatigue life of EDM mechanical parts [2–6]. In this study, the abrasive micro-blasting process was applied to remove the damaged surface layers and improve the surface integrity of WC–Co parts machined by wire EDM. Although the erosion properties of WC–Co bulk material have been researched extensively [7–15], there is a lack of study on the EDMed WC–Co surfaces.

Fig. 2. SEM micrographs of the surface and cross-section of a WC–Co part machined by wire EDM (CR: crater, RL: recast layer, and HA: heat-affected zone).
Abrasive blasting has been used extensively for surface treatment. This process has been applied to increase the surface roughness for higher coating adhesion strength [16]. With proper process setup, the abrasive blasting can remove damaged EDM surface layers and introduce a new surface layer with desirable compressive residual stresses [11,17–22]. Applications of blasting process to modify EDM surface layers have been investigated by Lee and Zhang [20] for Sylon 501, Deng and Lee [21] for Al₂O₃/TiC and Si₃N₄/TiC, and Lee and Deng [22] for Al₂O₃/TiC/Mo/Ni using 20–40 and 40–60 μm size Al₂O₃ abrasive. In this study, SiC abrasive with smaller particle size was used.

Micro-blasting using fine abrasive media is particularly suitable for microfabrication and surface treatment of micro mechanical components [23]. In contrast to conventional erosion by large-scale particles, no strength degradation occurs on the micro-blasted surfaces of ceramic materials [24]. The EDM process, which generates small cutting force, is ideal to machine micro features [25,26]. The fine abrasive carried by adequately high air pressure enables the micro-blasting process to modify the EDM surface on micro mechanical components. An example of the application of SiC micro-blasting of a micro-shaft is illustrated in Fig. 3. The EDM surface and its close-up view, which exhibit cracks, bubbles, and other thermal damages, are shown in Fig. 3(b). This surface is modified and exhibits more uniform texture after 5 s of blasting.

This paper presents a systematic study on micro-blasting of EDMed WC–Co surfaces using fine SiC abrasive. Results of the surface roughness, surface texture generated during blasting, and erosion wear rate are discussed.

2. Sample preparation and experimental setup

The work-material used in this study is the WC–Co composite, which consists of 1 μm size WC particle in 10 wt% Co matrix. This material has 92 Re hardness, 3.4 MPa transverse rupture stress, and 14.5 specific density. The WC–Co work-material was cut in a Brother HS-5100 wire EDM machine using 0.25 mm diameter brass wire. Two types of EDM WC–Co surfaces, designated as rough cut and fine cut, were prepared for blasting experiments. Fig. 2(a) and (b) shows SEM micrographs of the rough cut and fine cut surface, arithmetic average surface roughness (Rₐ), and subsurface cross-section. The process parameters and material removal rate of the rough and fine cuts are summarized in Table 1. Under the same spark cycle (28 μs), the rough cut has longer pulse on-time (14 μs), larger crater, rougher surface, higher material removal rate, and thicker recast layer and heat-affected zone.

Blasting and erosion wear experiments were conducted on a Mangum blasting machine, manufactured by Hess & Associates Inc. The machine used a venturi-type blasting gun with a 6.35 mm inner diameter Al₂O₃ nozzle. Since the duration of blasting was short and limited number of experiments was conducted, the nozzle wear was not a prob-
A time-control device was build to enable the blasting with a fixed period of time. The SiC abrasive was selected due to its high hardness. Two types of SiC abrasive, designated as Abrasives A and B, were used. Abrasive A, as shown in Fig. 4(a), was a mixture of particle sizes of 4–8, 6–12, and 10–20 μm, which corresponded to 1200, 1000, and 800 ANSI mesh, respectively. As shown in Fig. 4(b), Abrasive B was only 1000 ANSI mesh with particle sizes in the range 6–12 μm. All tests were conducted at 90° incident angle (normal incidence). The air pressure of 0.138 and 0.276 MPa was selected. Using the two-disk method [27], the particle speed for Abrasives A at 0.138 MPa was about 100 m/s. Particle speed at 0.276 MPa was expected to be higher, however, the apparatus used in this study was unable to accurately measure the high particle speed at this pressure.

Two sets of experiments were performed. One was focused on measurements and observations of surface integrity and roughness. Three blasting tests with a 5 s increment in blasting time were conducted. The other set of experiment was aimed at investigating the weight reduction and erosion wear rate. Three tests with 10 s blasting time increment were carried out. Table 2 lists process parameters used in the two sets of experiments. In summary, 24 (2 × 2 × 2 × 3) tests were carried out in the surface integrity experiment and 6 (2 × 3)

Table 1

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Rough cut</th>
<th>Fine cut</th>
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<tbody>
<tr>
<td>Spark cycle (μs)</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Pulse on-time (μs)</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>Axial wire speed (mm/s)</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>Gap voltage (V)</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>Material removal rate (mm²/min)</td>
<td>5.5</td>
<td>0.16</td>
</tr>
</tbody>
</table>

a Cutting a 6.35 mm thick plate.
b Removing a 50 μm surface layer.

tests were conducted in the erosion wear rate experiment. Results of these experiments are presented in the following two sections.

3. Results and discussion

3.1. Surface roughness

Fig. 5 shows results of arithmetic average surface roughness Rₐ for the 24 tests conducted in the surface integrity and roughness experiment. Before the blasting test (0 s), as shown in Figs. 2 and 5, Rₐ equals 1.34 and 0.83 μm on the rough cut and fine cut surface, respectively. The surface finish was improved over time and eventually reached a stationary level, when the recast layer and heat-affected zone had been removed. The trend to reach steady-state surface roughness can be seen in Fig. 5. For Abrasives A and B, the Rₐ is approaching 0.7 μm at longer blasting times.

The Abrasive A with larger size particles and/or high air pressure (0.276 MPa) removed the recast layer faster and reduced the surface roughness of rough cut parts more efficiently, as shown in roughness charts (Fig. 5) and SEM micrographs (Figs. 6–9). The EDM fine cut surface may be deteriorated by very short blasting time (5 s) and reached the stationary level at longer blasting time (15 s) using Abrasive A and high air pressure, as shown in Fig. 6.

Table 2

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Surface integrity test</th>
<th>Erosion wear rate test</th>
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</thead>
<tbody>
<tr>
<td>Abrasive</td>
<td>A and B</td>
<td>A</td>
</tr>
<tr>
<td>EDM surface</td>
<td>Rough and fine cut</td>
<td>Rough cut</td>
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<tr>
<td>Air pressure (MPa)</td>
<td>0.138, 0.276</td>
<td>0.138, 0.276</td>
</tr>
<tr>
<td>Blasting time (s)</td>
<td>5, 10, 15</td>
<td>10, 20, 30</td>
</tr>
</tbody>
</table>

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3.2. Surface layers

The surfaces of the wire EDMed WC–Co parts had the surface recast layer and sub-surface heat-affected zone, generated by the high local temperature during machining. The recast layer, also called thermally damaged layer, had craters and thermal cracks and bubbles, as shown in Fig. 2, which deteriorates the surface finish and reduced the wear resistance and fatigue life of the EDMed parts.

SEM was used to examine the surfaces and sub-surfaces of the WC–Co parts to investigate the effect of the micro-blasting. The selected SEM micrographs, shown in Figs. 6–9, indicated that the recast layer was eventually removed after 5 and 10 s for EDM fine cut and rough cut parts, respectively. Longer blasting duration also removed the heat-affected zone and reached a steady-state material removal in the bulk WC–Co material.

3.3. Surface texture

SEM micrographs of the fine cut surfaces blasted by Abrasive A at 0.276 MPa pressure are shown in Fig. 6. As shown in Fig. 6(a), after blasting by 5 s, ridges that manifest crater edges observed in Fig. 2(b) can be seen. During the spark erosion, the molten material was splashed and accumulated to form the crater edges. Micro-blasting erodes the damaged recast layer and exposes the crater edges as the ridge pattern after the first 5 s of blasting. Evidently, these ridges contributed
to the temporary increase in \( R_a \) at the beginning of blasting, i.e., the maximum in the curve in Fig. 5(a) (open triangles). As shown in Fig. 6(b and c), these ridges gradually disappeared after 10 and 15 s of blasting. The cross-section surface showed the recast layer was removed after 5 s of blasting, only a shallow residual of heat-affected zone remained. After 10 s of blasting, the heat-affected zone was also removed. A similar ridge pattern could be seen on all of the blasted fine cut surfaces, though not necessarily as pronounced as that seen in Fig. 6.

Close-up views of Fig. 6(b) are shown in Fig. 7. The boundaries between the 1 μm size WC grains are not easily identified. Furthermore, there are no distinct cleavage facets indicative of individual brittle fracture events. Since the erodent particles have sizes in the range of 10–20 μm for Abrasive A, one could expect that erosion impact events at the high velocities used would overlap a large number of WC grains. The erosion mechanism for the blasting conditions used is therefore a composite-like removal of multiple WC grains per impact facilitated by plastic flow in the surrounding Co matrix. This is in contrast to the case reported by Anand and Conrad [13] where small erodent particles at low velocity produce individual impacts in single WC grain and a clear brittle-like erosion response.

SEM micrographs of the surface and subsurface cross-section under the same blasting condition as in Figs. 6 and 7,
but on the rough cut surfaces, are shown in Figs. 8 and 9. As shown in Fig. 8(b and c), a surface texture with many small, less than 1 μm size cavities that follow the pattern of crater edges, as seen in Fig. 2(a), can be observed. The 2 μm tip radius diamond stylus for the profilometer surface roughness measurement would not detect these cavities and the $R_a$ results in Fig. 5 would not be affected.

Fig. 9 shows close-up views of Fig. 8(b). From the overall pattern of distribution of these features, it can be assumed that the source of the cavities is also related to the crater formation during EDM spark erosion. For the rough cut condition, the energy density in each spark erosion was higher and more molten material was generated in each spark erosion. Bubbles and cavities on the rough cut surfaces (Fig. 2(a)) are therefore larger and more prominent than those of the fine cut surfaces (Fig. 2(b)). As shown in Fig. 8, these cavities were exposed in the first 5 s of blasting and accentuated in the follow-up blasting at 10 and 15 s. Most cavities disappeared when the process reached steady-state after 30 s blasting, as shown in Fig. 10. The remaining few cavities on the blasted surface

Fig. 10. Erosion wear rate of SiC micro-blasting on wire EDM WC–Co.
are possibly due to the porosity in the original WC–Co mate-
rial. This can be validated by examining the close-up views in
Fig. 11. The surface texture, disregarding the cavities and porosity, is similar to that in Fig. 7(b). The boundaries be-
tween WC grains are not easily identified, and there is no
distinct cleavage facet to indicate the individual brittle frac-
ture of WC.

In general, all rough cut EDM surfaces exhibited similar pattern of cavities, as seen in Figs. 8 and 9. All fine cut EDM surface showed a ridge pattern similar to that in Figs. 6 and 7. These observations manifest the formation of ridges, bubbles, and cavities in EDM recast layers. Further investigations are necessary to establish the details of the formation mecha-
nisms.

3.4. Erosion wear rate

The erosion wear rate experiments were conducted by blasting a 6 mm × 6 mm rough cut EDM WC-Co surface using Abrasive A for 10 s time increments and then mea-
suring the weight loss. A blasting time increment of 10 s was used in order to measure the steady-state erosion wear rate. Due to the limitation of the EDM workpiece sizes, this test setup was different from the standard erosion tests specified in ASTM G76-95 [28], in which a larger surface area should be used.

As shown in Table 2, six erosion wear rate tests were car-
rried out at 0.138 and 0.276 MPa air pressure with 10, 20, and 30 s blasting time. Two parts were blasted and the weight loss was measured in each test. The average weight loss was di-
vided by the weight of SiC abrasive blasted to calculate the erosion wear rate. On average, 31 and 46 mg/s of Abrasive A were blasted at 0.138 and 0.276 MPa air pressure, respec-
tively, during a 10 s interval.

Fig. 12 shows the experimental results of the cumula-
tive weight reduction and erosion wear rate. A higher erosion wear rate was observed in the first 10 s than the following two blasting durations. This transient can be attributed to the materials removal associated with thermal cracks and bubbles. These defects result in lower erosion wear resistance of the recast layer. At 30 s, when the erosion rates approach steady-state, the 0.0013 and 0.0067 g/g ero-
sion wear rates are higher but comparable to that reported by
Beste et al. [12] and Anand and Conrad [13].

4. Concluding remarks

The abrasive micro-blasting process was used to improve the surface integrity of WC-Co samples machined by wire EDM. Two sizes of SiC abrasive, two levels of air pressures, and three time durations were applied to blast EDM rough cut and fine cut WC-Co surfaces to explore effects of blasting parameters on the surface integrity. The recast layer and heat-
affected zone can be removed by SiC micro-blasting in very short times using easily achieved erosion conditions. Larger size abrasives and higher air pressure produce higher erosion wear rate and reduce the EDM surface roughness more effectively. The unique surface texture, related to the crater formation of the recast layer, has been revealed on SEM micrographs and studied to help understand the influence of the micro-blasting process on the surface integrity of the wire EDMed WC-Co parts.

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