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Development of morphology in laser dressed grinding wheels

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ABSTRACT

Purpose: The paper describes the development of faceted morphology in laser dressed grinding wheels.
Design/methodology/approach: The approach used in the paper is based on locally melting a vitrified grinding wheel and measuring features such as grain size, cooling rate and melt depth as a function of laser fluence and relating these measures to the morphology shown in the microstructures presented in the paper.
Findings: The findings of this course of research lead the authors to believe that a specific morphology is dependent upon cooling rate and laser fluence.
Research limitations/implications: The findings show that further research is required to fully understand how certain morphologies form as a function of cooling rate and laser fluence. It should be noted that morphologies observed in laser processed grinding wheels include cellular and fully dendritic morphologies in addition to faceted vertices.
Practical implications: The results imply that laser dressed grinding wheels can be used for machining different materials at different grinding speeds. The paper also shows that much development is needed to identify laser processing conditions that are appropriate for different workpiece materials.
Originality/value: The paper shows that different morphologies can be used to machine workpiece materials under different conditions. The originality in the paper is focused on the formation on minute cutting points using increasing laser fluences.
Keywords: Machining; Dressing; Lasers; Grinding wheels

1. Introduction

Surface modification with lasers is an established technique for changing surface properties [1-5]. This is especially so for vitrified grinding wheels. Grinding wheels are composed of abrasive grains bonded together with a vitrified glassy bonding agent with a contained level of porosity. Each particle contributed to removing a small amount of material. The sharpness of the grain is extremely important to removing material. Major efforts have been made by Purdue University and Micro Machinists, LLC., to develop a laser dressing method that is capable of producing a superfinishing wheel by locally modifying the surface of alumina grains. The method involves locally melting and solidifying the surface as opposed to direct ablation of the surface constituents. This technique avoids the damage created by mechanical dressing techniques [5-10]. It should be noted that mechanical dressing techniques induce fractures in the abrasive grain and in the bonding system that coats the individual grains, the grains and bonds then become weakened. High power lasers can induce the melting and evaporation of bonding between grains that allows the alumina to melt at approximately 2300K, which results in finely defined cutting edges that at located at the vertices of re-modelled alumina grains. As the features are on the microscale, they are well suited to microscale grinding operations. This paper describes the changes in morphology of a vitrified grinding wheel using a new dressing procedure.

2. Experimental procedure

The experimental procedure involved applying a focused laser beam on to the surface of a vitrified grinding wheel that was supplied with a vitreous bond bonded to chromia-doped alumina. A polished cross section of the grinding wheel is shown in Figure 1.

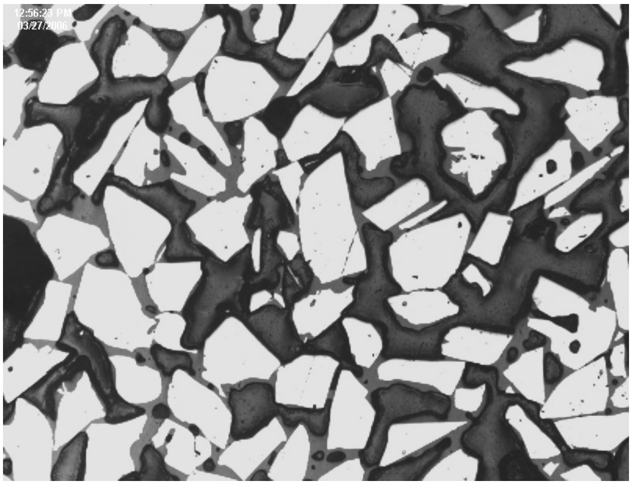

Fig. 1. Polished cross section of vitrified alumina grinding wheel

The average grain size was 220µm that is known as 60 grain size in the industry and has a 6 structure number and a medium grade structure. The surface of the grinding wheel was treated with a 4kW continuous wave Nd-YAG laser at a scaning velocity of 10 cm/min. The wheel was dressed in parallel tracks and was dressed in steps of 100W from 1000W to 2000W. The samples were characterized by polishing using the standard techniques for preparing SEM specimens. The samples were sputtered with gold so that a conductive surface was obtained. Maximum melt depth was obtained at low magnifications and was measure at five points until an average value was determined for each laser power (and associated fluence) value.

3. Experimental results and discussion

The effects of laser dressing are quite remarkable. The surface layer is composed of finely distributed cutting points on the surface of a highly porous layer of abrasive. The wheel is capable of removing bulk material and fine scale material. The generation of macro and microscale detritus has tremendous potential for precision grinding applications. Studies of grinding tool steels have provided information regarding the generation of fine scale surfaces and the effect on the mode of fractures of grinding wheels [10]. Multi-faceted grains produced allow the production of individual pyramidal indenters, which combined with sideways sliding motion can produce a surface capable of fine grinding. The surface layer was compared of α-alumina grains without the bonding provided by the vitrified bonding system. This observance was confirmed by XRD analysis [10]. The detection of bonding material was not observed probably due to the very small amount of bonding used in the grinding wheel. The performance of the grinding wheel is determined by grain size and grain morphology and this study measured the average diagonal distance of polygonal grains. The increase in laser fluence increases the grain size of the faceted grains because the thermal source tends to change the nature of the surface of the grinding wheel. To understand the behaviour due to processing, cooling rate calculations have been conducted based on a simple one-dimensional thermal model. The uniform nature of the grinding wheel molten surface allows one to use such a model. A single line of flow is considered even though parallel lines of flow were deposited. However, the distance between the two and the time duration between laser processed tracks allowed us to use the one-dimensional model. The low thermal conductivity of alumina limits the effect of heat flow to adjacent tracks. The governing equation is [11]:

$$\frac{\partial T(x,t)}{\partial t} = \alpha . \frac{d^2 T(x,t)}{dx^2} \tag{1}$$

Where α is the thermal diffusivity of the material, k is the thermal conductivity, C_p is the specific heat capacity, and ρ is the density of the material. The effective thermal conductivity is provided by using Lees' disc apparatus and is described by Jackson et al. [12]. The model presented [12] provides the temperature distribution s from which the temperature gradient, G, and the velocity of the liquid/solid interface, R, can be calculated by a method explained in reference [12]. The cooling rate is a product of G and R, and a the secondary dendrite arm spacing is given by the following equation [13],

$$SDAS = A(T_c)^{-n} \tag{2}$$

Where A and n are constants. The grain growth depends on nucleation and growth of which the conditions of growth are dependent on the cooling rate. The laser fluence decreases cooling rate as it increases in value and results in large faceted grains. This is in agreement with solidification theories. As the grain size increases, the effectiveness of the surface layer appears to decrease in terms of the surfaces ability to remain intact on the surface of the grinding wheel. Therefore, an optimised thickness must be found depending on grinding parameters. The thickness of the layer appears to occur at a fluence of around 700 J/cm^2, or approximately 1850W. The maximum temperature at this point is attained that explains why the melt depth does not increase any further. Any further power provided by the laser would be used to evaporate the material that is already molten. Once initiated, the evaporation of material would not affect the melt depth at the surface with a further increase in laser fluence. In addition to that statement, as the temperature increases, the thermal conductivity of the material decreases fairly rapidly that tends to limit the depth of the molten layer.

Figure 2 shows the surface of the laser processed grinding wheel. The microstructure shows the early formation of faceted alumina grains at approximately 380 J/cm^2 and produces a uniformly distributed structure of pyramidal grains together with an assembly of smaller cuboid-shaped crystals.

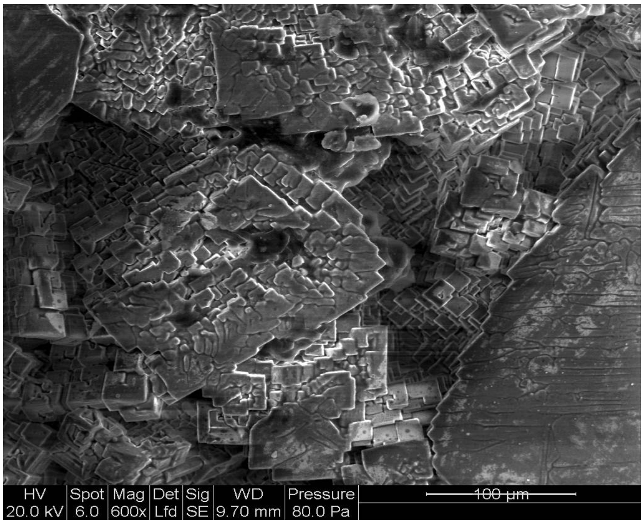

Fig. 2. Formation of faceted surface grains by focused laser beam. The individual small cuboids are shown surrounding the larger grains.

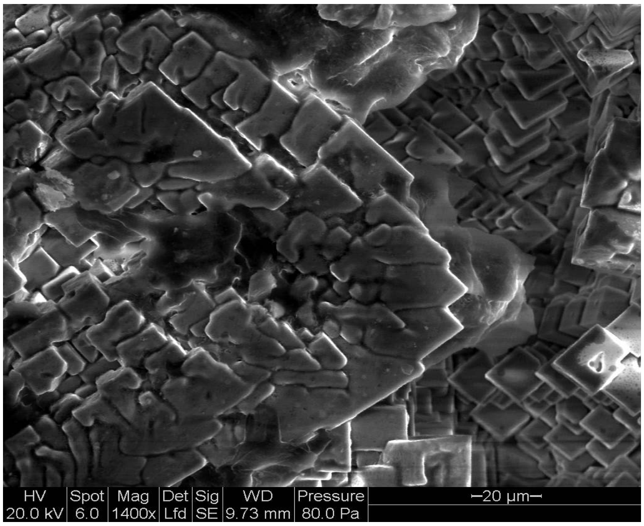

Fig. 3. Assembly of small cuboids that have grown in the opposite direction of heat flow.

The formation of distributed crystals may be a function of the amount of initial porosity on the surface of the grinding wheel that causes a high rate of solidification of the molten flows to occur between the interstices of the pores. Faceted growth of grains on the surface of the grinding wheel is due to competitive growth of a variety of various crystal planes that determine the energetically favourable shape of the crystal during solidification. The magnified image of Figure 2 is shown in Figure 3 and shows the smaller cuboidal crystals that may have formed due to the high solidification rates associated with being close to surface porosity. The formation of dendrites due to rapid solidification rates is associated with the laser processing regime. The cuboidal crystals are the parts of the dendrites that grow toward the surface of the sample in the directions opposite to heat flow. At the end of solidification, the assembly of stacked grains (Figure 3) forms at the laser dressed surface. As laser fluence increases the cooling rate decreases resulting in a densely packed assembly of cuboid crystals. At low laser intensities, the packing is less and provides microporosity that is useful for the evacuation of swarf.

Cooling rates of the order of hundreds of ^{O}C per second are observed during laser dressing of vitrified corundum grinding wheels. High laser power tends to generate slower cooling rates because of the thermal properties of these complex porous ceramic materials. The observed solidification structures tend to be dendritic at the center of the laser-processed track, and columnar near to the edges of the track. Analyses of the laser processed tracks showed a preferred growth of grains along the c-axis of alumina and in a direction opposing heat flow [14]. In association with x-ray diffraction analysis and pole figure analysis, preferred orientation favours growth on the (110) planes that are parallel to the c-axis in the hexagonal alumina cell. Competitive growth of grains takes place in the re-solidified layer during which time the grains with their c-axes not orientated from the center of the track are prevented from growing in their favoured directions [15]. Initial grinding experiments suggest that laser-dressed grinding wheels cut freely but produce lower surface roughness on hardened steel workpiece materials owing to the predominance of oriented vertices of α-alumina that remove very small amounts of material even at an increasing preponderance of feed.

4. Conclusions

A novel way of dressing vitrified grinding wheels using a focused laser beam on the surface of the grinding wheel is suggested and is based on the solidification microstructures formed using a focused laser beam. Very high solidification rates associated with laser dressing results in a refined surface that is composed of the formation of multi-faceted grains. The detailed investigations have found that surface grains increase in size as the laser fluence is increased. This is attributed to slower cooling rates. The melt depth is limited by further increases in temperature and this may be due to the decreased heat conduction at much higher temperatures. Therefore, the size and shape of the facets can be controlled, which makes lasers useful tools for laser dressing.

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