Evaluation of Grinding Characteristics of Thermal Spraying Ceramics Film*

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This paper discusses the grindability of sprayed coatings of Al₂O₃(-TiO₂). The actual grinding action was investigated experimentally by surface grinding using a resinoid diamond wheel with different particle sizes and concentrations.

The maximum height of the grinding surface was lower when the grain size of the wheel was larger and the degree of concentration of the wheel was higher. The abrasion of the grinding wheel was not due to the abrasion by the abrasive grain, but to a selective removal of the surface grinding using a resinoid diamond grinding wheel with different particle sizes and concentrations.

1. Introduction

Sprayed ceramics film is a lamination of fused particles sprayed onto a substrate surface under high-temperatures and pressures. This product is significantly different from sintered ceramics in that it has remarkable anisotropic properties.¹⁻⁴ The spraying technique can be easily applied to a broad range of products with large surface areas and irregular configurations, and the formation of films is particularly applicable machine parts where the machining of the surface of sprayed film is essential. The authors have investigated the machinability of films of sprayed ceramics and discovered that finishing is possible.⁵ However, the peeling and falling off of laminated sprayed particles, along with the generation of inter-granular fine cracking that occurs during machining depending on the machining conditions makes it very difficult to obtain a flat machined surface with this material texture. Normally, in the case of machining (grinding) of brittle materials such as ceramics, scars generating continuous chips are few, and the machined surface mostly consists of deformation due to peeling, falling and friction. Therefore, in order to make it a high-precision machined surface, it is to do under the machining condition that peeling and falling of the thermal spraying particle do not do.⁶⁻⁸

In the present study, of the grinding phenomena of various Al₂O₃-TiO₂ sprayed ceramics films, surface grinding experiments using a resinoid diamond grinding wheel with different grain size and concentrations⁹ were carried out. The grinding force, conditions of the ground surface and conditions of the grinding wheel surface, influenced by the increase in frequency of grinding, were also tracked. The effects on the structure of the sprayed film during the grinding process were then investigated.

2. Experimental Apparatus and Method

The grinding experiments were carried out using a carbide tool material grinding machine and based on the surface grinding method to observe two components of the grinding process: conditions for the creation of a ground surface, and the surface condition of the grinding wheel. Figure 1 is an outline diagram of the Al₂O₃ and Al₂O₃-TiO₂ ceramic powders (four types: WAL, GAL, AT91, and AT64) used as the spraying materials. The chemical compositions, range of particle size, and hardness status of the surface before grinding are shown in Table 1. Resinoid diamond grinding wheels were used in the experiments. The grain size of the grinding wheel was 140, 400, 800 each in degree of bond P, and the concentration was varied at 25, 50, 75, and 100. The wheel speed (V) was set to 1,860 m/min, the table feed rate (F) to 2.7 m/min, and the set depth of cut (h) per one grinding

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was varied in the range of \( 5 \sim 40 \mu m \). The set depth of cut \( (h) \) at grinding was obtained using a laser displacement gauge fixed to the headstock of the grinding machine. Table 2 shows the details of each experimental condition.

Changes in two components of the grinding force \( (F_t: \text{Tangential grinding force}, F_n: \text{Normal grinding force}) \) were detected by an elastic octagonal ring-type grinding dynamometer and processed by a dynamic strain meter and personal computer. The true depth of cut \( [\Delta h: \text{depth actually removed by grinding}] \) was calculated from the results by measuring the height of the grinding surface taken by the laser displacement gauge before and after grinding. Right angle surface roughness with respect to the grinding direction was measured using a stylus surface roughness tester and expressed by the maximum height of roughness \( (R_z) \). Furthermore, the status of the ground surface was observed by a scanning electron microscope. The status of the grinding wheel surface was evaluation using six predetermined measuring points on the grinding wheel surface connected to the grinding times \( (n) \) of 200, while the set depth of cut \( (h) \) was maintained at \( 20 \mu m \) and observed by a microscope mounted on the grinding machine table.

3. Results of the Experiments and Discussions

3.1 Changes in the grinding force

Ceramics sprayed film can be machined comparatively easily with diamond tools.\(^5\) However, this is not an optimum option machining method to obtain a high-precision finished surface and grinding processing is required to achieve such a result.

Since grinding processing is a fine cutting process that uses multiple cutting edges, it is effective for finishing. However, with sprayed film, the binding power between particles constituting a film is not of sufficient strength and there are also heterogeneous areas. In addition, since the fine pores specific to sprayed films are scattered, problems are anticipated during grinding such as substantial peeling or falling off of sprayed particles at the cutting edge during grinding. Therefore the machining phenomena should be clarified in detail before evaluating the machining materials with special textures as mentioned above. The change of the grinding force is examined in the initiative in order to clarify the grindability.

Figure 2 shows changes in two components \( (F_t, F_n) \) of the grinding force due to an increased frequency of grinding in which three types of sprayed ceramics films of WAL, AT91, and AT64 were subjected to surface grinding using a grinding wheel with a grain size of 140, a concentration of 25, and with a set depth of cut \( (h) \) of 20 \( \mu m \). The grinding force is greatly affected by the wear of the grinding wheel, loading and changes in the grinding wheel surface due to the self-sharpening. Two components of the grinding force show a tendency to increase, although small in amount, with an increase in the frequency of grinding, while repeating up/down fluctuations with a shorter cycle. In the grinding conditions used in the current experiments, with respect to two components of the grinding force, the normal grinding force \( F_n \) shows greater values than the tangential grinding force \( F_t \). Although some variations are caused in the grinding force of sprayed ceramics AT91, significant changes attributable to a difference in the workpieces are not recognized.

Figure 3 shows changes using a grinding wheel with a concentration of 100. When compared to using a concentration of 25, the two components of the grinding force show a decrease and increase with longer cycle and with an increased frequency of grinding. In particular, the value of \( F_n \) shows the close value of 3 times in case of degrees of concentration of 25(Fig. 2), and it increases very much. This is considered to be due to the fact that as the concentration of the grinding wheel increases, the chip’s pockets become smaller. In addition, the abrasive grain-cutting edge interval is narrowed considerably, and as a result, chips that are now in powder form are not discharged, but instead buried into the chip’s pockets, thereby causing an extreme loading problem.

3.2 Status of the ground surface

Figure 4 shows the status of the ground surfaces as observed by a scanning electron microscope (SEM). The samples are of four types of sprayed ceramics after the grinding processing. On films with a lower TiO\(_2\) composition, such as WAL or GAL, the slight peeling and falling off of sprayed particles, as well as fine cracks that occurred frequently during grinding are noticed in various places. Also, many grain boundary exposed parts are recognized on the ground surface. This phenomenon occurs after on WAL that has a higher hardness, and on AT91 and AT64 which have a high TiO\(_2\) composition. In addition, the amount of peeling and falling off areas decreases, many scars due to the cutting and abrasion are generated on the ground surface, and...
increases nearly linearly as \( h \) increases. The values of \( R_z \) are in the range of 3 \( \sim \) 5\( \mu \)m at \( h = 10 \mu \)m and increases to 6.5 \( \sim \) 7.8\( \mu \)m at \( h = 40 \mu \)m. This tendency differs among workpieces and those with higher TiO\(_2\) compositions tend to exhibit a greater \( R_z \) value.

Changes in the surface roughness \( R_z \) compared to changes in the grain size of the grinding wheel are shown in Fig. 6. It is noted from Fig. 6 that \( R_z \) tends to decrease sharply as grain size increases and \( R_z \) in the range of 5 \( \sim \) 6.5\( \mu \)m with a grain size #150 decreases linearly to around \( R_z \) 1.5 \( \sim \) 2\( \mu \)m with a grain size #800.

Variations in surface roughness \( R_z \) due to chances in the concentration of the grinding wheel are shown in Fig. 7. A surface roughness in the range of \( R_z \) 7 \( \sim \) 8\( \mu \)m, with a concentration of 25, starts decreasing at a concentration of about 50 and drops to a \( R_z \) 3 \( \sim \) 4\( \mu \)m with a concentration of 100. This tendency is explained by the fact that since the abrasive grain-cutting edge interval decreases as the concentration increases, the number of active abrasive grains on the grinding surface has increased.

### 3.3 Relationship between the set depth of cut and true depth of cut

Generally, during the grinding processing, actual removal [true depth of cut \( (\Delta h) \)] does not take place in accordance with the set depth of cut \( (h) \), and is affected by relief, deformation, etc. of the grinding wheel, workpiece and the mechanical system. In addition to these causes, when grinding a sprayed film the effects resulting from the film texture are expressed. It is preferable the ratio of the set depth of cut to the true depth of cut \( (\Delta h/h) \) during the grinding processing should be close to 1 if machining accuracy and efficiency are considered. However, with workpieces of greater hardness a trend of extreme reduction in \( \Delta h/h \) due to the previously noted causes, results from a lower depth of cut (less than \( h = 10 \mu \)m). Conversely, with a longer depth of cut, the increase in the cut is brought about by an expansion of the peripheral area of the grinding point caused by an elevation of in grinding heat, that results in \( \Delta h/h \) being close to 1. However, this grinding state is unstable. In the current study of sprayed ceramics subjected to grinding processing, the effects of differences in grinding conditions on \( \Delta h/h \) were investigated. Figure 8 shows changes \( \Delta h/h \) in resulting from an increase in the grinding wheel concentration where
### 3.4 Changes in the grinding wheel surface with an increased frequency of grinding

Figure 10 shows the surface condition of WAL observed by a metallographic microscope after being ground using a grinding wheel with a concentration of 25, with an increasing frequency of grinding. In the figure, the frequency of grinding \( n = 0 \) represents the conditions of the grinding wheel surface after dressing using a grinding wheel of WA #120 after truing. This grinding wheel surface condition was decided to be the initial conditions for grinding experiments and the experiments were continued till \( n = 200 \). With a concentration of 25 and where the abrasive grain density is low, many scorings that formed during dressing are recognized in the area of bonding agent. At the initial stage of grinding with frequency of grinding of around \( n = 5 \), the area of bonding agent is scraped away by the workpiece and abrasive grains are partially exposed. When \( n = 40 \), almost all abrasive grains are completely exposed and some are about to fall off. Furthermore, when grinding is continued until \( n = 80 \sim 120 \), the wearing in the area of bonding agent is accelerated and exposes new abrasive grains. With \( n = 200 \), a large number of holes for retaining abrasive grains, which are formed after many abrasive grains in the portion of bonding agent have fallen off, are noted.

This phenomenon shows that the self-sharpening\(^{100}\) is done in the short period. Therefore, the abrasion of the grinding wheel progresses on the adhesion (the plugging phenomenon) of the ceramic powder to the chip pocket without recognizing almost.

Figure 11 shows a case where WAL is ground by a grinding wheel with a concentration of 100. Many abrasive grains fell off, are noted. Many abrasive grains in the portion of bonding agent have many holes for retaining abrasive grains, which are formed after many abrasive grains in the portion of bonding agent have fallen off.

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grain cutting edges can be confirmed at the initial stage of grinding \((n = 5)\). However, when using a grinding wheel with a concentration of 100, since the abrasive grain density is higher, no scar is found in the area of the bonding agent as is the case of the former concentration. Fine concaves alone appear and no scoring due to scratching is recognized. However, at about \(n = 30\) times, the chip pockets are formed on the grinding wheel, and the grinding wheel shows loading and glazing. After it \((n = 50, 90\) times\), the loading condition hardly is solved. Between \(n = 90\) and 154, the dug up portions where abrasive grains have fallen off are recognized throughout. At \(n = 200\), the abrasive grain state during dressing is not recognized at all and an excessive change in the grinding wheel surface is noticed. Observation of the photographs reveals that with this phenomenon, the chips cause abrasive grains to exert a greater force due to excessive loading and at the same time fracture is caused in part and is enhanced by an impact force during grinding, thereby promoting the falling off of abrasive grains. Accordingly, re-dressing the grinding wheel is necessary.

The resulting of observation of the grinding wheel surface indicates that in the case of a low concentration \((\text{concentration of } 25)\), the areas of the bonding agent are damaged excessively and the falling off of abrasive grains is remarkable. On the other hand, no loading phenomenon is generated. At concentrations of 100, the chips are buried into the chip’s pockets resulting in significant loading phenomenon. Also, abrasive grains fall periodically causing a break and promoting wear of the grinding wheel.

4. Conclusions

In order to elucidate the grinding phenomena of \(\text{Al}_2\text{O}_3\)-(TiO₂) ceramics sprayed film, the surface grinding behaviors by a resinoid diamond grinding wheel were investigated while the grain size and concentration of the grinding wheel were changed. Major results obtained are as follows:

1. Two components of the grinding force tended to repeat up/down fluctuations periodically with an increased frequency in grinding.
2. On the ground surface, areas ground by abrasive grain cutting edges and areas where grains have been peeled or fallen off thereby exposing the grain boundary are present in a mixed state. Furthermore, the greater the content of TiO₂, the less frequent is the occurrence of peeling and falling off.
3. The surface roughness \((R_z)\) of the ground surface increased as the set cut of depth increased, and decreased as the abrasive grain size increased. Furthermore, it decreased as the concentration became higher.
4. As for changes in the status of the grinding wheel with an increased frequency of grinding, the areas of bonding agent was selectively worn down during grinding, abrasive grains fell, and wear of the grinding wheel was enhanced. This phenomenon was more remarkable at lower concentrations. However, the loading phenomenon occurred with a higher concentration.
5. Wear of the grinding wheel was promoted significantly at the initial stage of grinding except under some conditions. After that, wear increase was nearly linear, though modest, with an increase in the frequency of grinding. This is attributable to the profile of the cutting edges after dressing. The frequent and repeated breaking and falling off of abrasive grains also contribute to this phenomenon.

REFERENCES

9. Concentration: With a diamond CBN wheel, the concentration used as an index to ascertain the amount of abrasive grains is contained in the abrasive grain layer. A grain percentage of 25% by volume (4.4 ct/cm³) is defined as a concentration of 100 and is normally found to be in the range of 20 ~ 200.
10. Self-sharpening: Also referred to as self-dressing, which means that dressing takes place automatically by the fracture or falling off of abrasive grains brought about by the grinding force exerted on the abrasive grains during grinding.