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Short communication

A method to quantify the drilling machinability of machinable ceramics from the viewpoint of preventing chipping

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Abstract

A method to quantify the drilling machinability of machinable ceramics is proposed from the viewpoint of preventing chipping in the rear side of the specimen, and its feasibility has been tested by using a 100 μm-diameter drill and two types of BN-containing machinable ceramics sintered by hot pressing in a laboratory-scale instrument. Based on the optical microscopy observation of the drilled holes at the varying feed velocity V (mm/min) at given rates of the spindle rotation R (10k–40k rpm), there exists a critical boundary in V–R space, above which chipping transpires and below which no chipping occurs. For the investigated specimens, the critical boundary is roughly linear in the investigated range of R. The position and shape (linear or non-linear) of the boundary may be dependent on material type as well as on the geometry of the drill. The fitted equation of the critical boundary in the V–R space may serve to quantify the drilling machinability of machinable ceramic materials.

Keywords: B. Optical microscopy; C. Mechanical properties; D. Nitrides

1. Introduction

There has been high interest recently in the fabrication of machinable ceramics [1–3]. Machinability is a measure of the ease with which a material can be shaped with the aid of cutting or abrasive tools. Despite the establishment of such a qualitative definition, the quantification of the machinability has never been a simple task. This has naturally led to the development of various factors to assess ceramic machinability based on material removal [4–7] and the associated mechanism [8], surface damage [9,10], single point abrasion [11], and combined material properties as functions of elastic modulus, Vickers hardness, and model I fracture toughness (K_{IC}) [12,13]. Yet, regardless of such existing factors to assess the machinability of ceramics, no particular factor has been regarded as dominant [14], possibly because of the differences in the fabrication process in achieving the desired final shape and the associated material response. Unlike other material properties such as elastic modulus, strength, and K_{IC}, it has thus far not been particularly easy to determine how much the machinability of a certain material is superior or inferior to others on a quantitative base. The difficulty of quantitative assessment of the machinability of ceramics is well documented [14,15].

The industrial needs for the drilling of machinable ceramics have been growing rapidly. Among the wide areas of the needs, the drilling of the machinable-ceramic guide plate of the probe card used for semiconductor chip testing is now receiving much interest: drilling of approximately 10^4 holes per guide plate is required [16]. The chipping of any single hole among numerous holes may lead to the failure of the product that is being drilled. Thus, the assessment of machinable ceramic materials on a quantitative base is very important. The purpose of the current study is to propose a practical methodology for assessing the drilling machinability of ceramics on a quantitative base in light of preventing chipping, and to investigate its feasibility.

2. Proposed methodology

It is generally experienced during the drilling operation of machinable ceramics that the chipping in the back side of the

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specimen is more apparent as the feed velocity V (m/min) of the drill increases at a given rotation rate of the spindle R (rpm). The increase of the feed velocity V at a given rate of the spindle rotation R means the increase of the feed rate f (m/rev), because of the relation, $V=fR$.

Such an experienced phenomenon of enhanced chipping by the increased feed velocity V and increased feed rate f is schematically illustrated in Fig. 1. In illustrating the experienced phenomenon in Fig. 1, an existing experimental study by Sentoku and Yamada [17] has been utilized. In their study, the degree of chipping (DOC) at a number of (V, f) combinations was quantified by measuring the thickness of the chipped area in the rear side of the specimen. Their investigated (V, f) drilling conditions have been transformed to (V, R) sets in the current study, and are illustrated in Fig. 1.

From the generally experienced phenomenon (which is also supported by the existing study [17]), it is proposed that a critical boundary in the V–R space exists, above which the chipping occurs and below which there is no chipping, as marked in Fig. 1. In this figure, the critical boundary in V–R space was simply assumed to be a linear line, while the linearity or non-linearity needs to be checked by way of experimentation. The critical line is drawn to have a positive slope because the feed rate f decreases (which decreases DOC) as the rate of the spindle rotation R increases at a given feed velocity V. The position of the critical boundary in the V–R space may serve the quantitative measure of the drilling machinability of machinable ceramic materials; the higher the position is, the higher the drilling machinability will be in light of the prevention of chipping.

3. Experiment

An appropriate quantity of Si_3N_4-BN (sample S)- and AlN-BN (sample A)-based powder batches were mixed by ball mill in ethanol medium, dried, and hot pressed in a laboratory-scale hot press instrument at 1800 °C and 20 MPa for 2 h. The samples were machined to $10 \times 10 \times 0.4$ mm^3 for the drilling operation. The diameter of the drill used in this study was 100 μm (Model 30-3031TA, HAM Precision Tools Andreas Maier, Inc., Pewaukee, WI, USA). The investigated range of rate of the spindle rotation (R) was 10,000–40,000 rpm, and the feed velocity (V) was in the range of 0.5–15 mm/min (Model HS430L, Sodick Co., Ltd., Yokohama, Japan) at an interval of 1 mm/min, although an interval of 0.5 mm/min was also employed when necessary. Five holes were drilled at a given (V, R) condition. The occurrence of the chipping was judged by the defocusing of the microscope image of the chipped area near the drilled hole at the rear side of the specimen (Figs. 2 and 3). If any single hole out of five holes at a given (V, R) condition was defocused, the given (V, R) condition was judged to be the chipped condition.

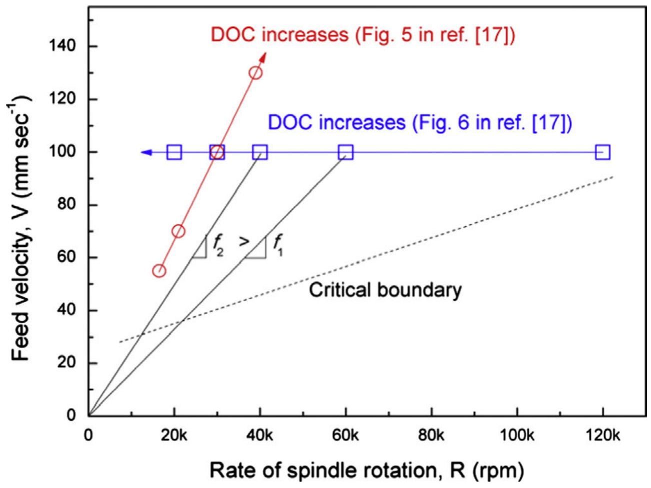

Fig. 1. Schematic illustration for the experienced phenomenon of increased degree of chipping (DOC) with increased feed velocity V and with decreased rate of spindle rotation (increased slope, i.e., the increased feed rate f).

4. Results and discussion

The optical micrographs of the fabricated holes in the rear side of samples S and A by the drill with the diameter of 100 μm are shown in Figs. 2 and 3. In these figures, the

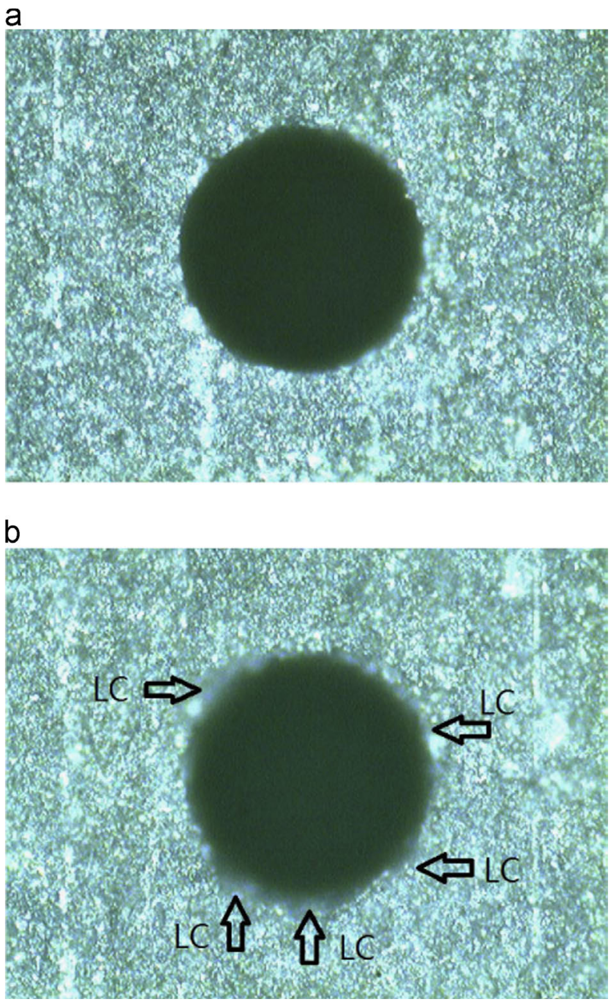

Fig. 2. Optical micrographs for the holes formed in sample S by the drill diameter of 100 μm. (a) $R=20{,}000$ rpm and $V=2$ mm/min, (b) $R=20{,}000$ rpm and $V=4$ mm/min. LC denotes localized chipping.

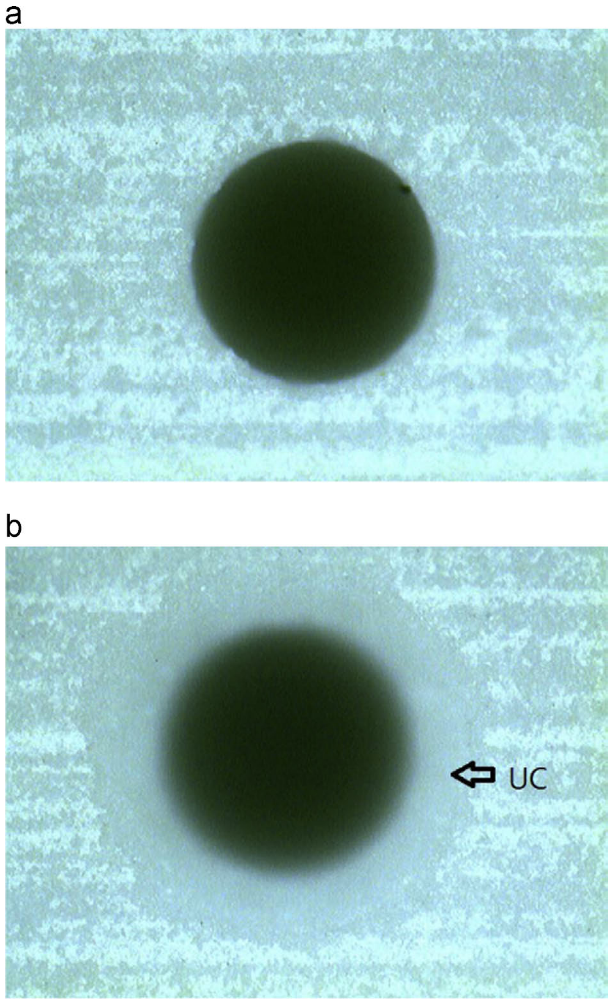

Fig. 3. Optical micrographs for the holes formed in sample A by the drill diameter of 100 μm. (a) $R=30{,}000$ rpm and $V=5$ mm/min, (b) $R=30{,}000$ rpm and $V=7$ mm/min. UC denotes uniform chipping.

specimen surface position sufficiently far away from the edge of the hole was focused. Thus, the defocused areas (Figs. 2(b) and 3(b)) result from the difference of the height of the specimen surface caused by the chipping. The height of the chipped area (defocused) is lower than the specimen surface, which is focused. In Fig. 2 (sample S), it is seen that the increase of the feed velocity V from 2 to 4 mm/min at a given rate of the spindle rotation R (20k rpm) yields the apparent evidence of chipping (the defocused area near the hole boundary). In sample S, the chipping area is localized at some locations along the periphery of the drilled hole marked as LC (localized chipping). The phenomenon of the localized chipping represents the characteristics of sample A in the investigated (V, R) data sets in the current study.

In sample A (Fig. 3), as the feed velocity V increases from 5 to 7 mm/min, this sample also forms the defocused peripheral area due to the chipping at a given rate of the spindle rotation R (30k rpm). Unlike with sample S, the chipping occurs uniformly along the periphery of the drilled hole (marked as UC: uniform chipping), and this phenomenon of uniform chipping represents the characteristics of sample A in the investigated

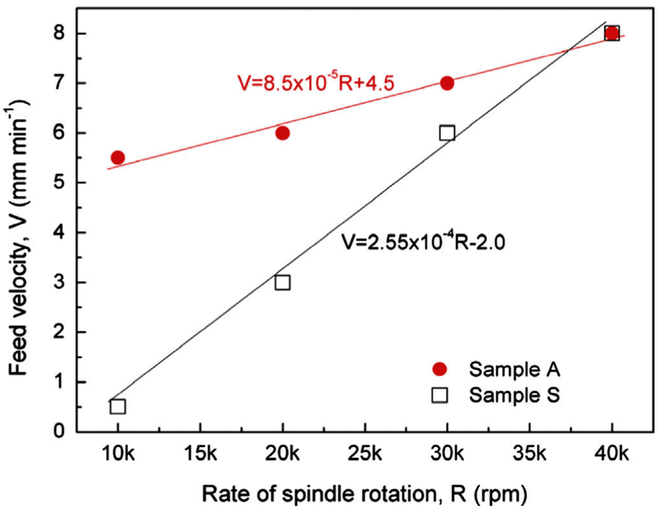

Fig. 4. Critical boundaries for sample A and sample S determined by the onset of chipping in the drilling operation. Chipping takes place at the area from and above the boundary line and no chipping occurs below the boundary line.

(V, R) data sets. A comparison with sample S shows the mode of the chipping fracture (LC of UC) to be material dependent rather than fabrication-condition dependent in the investigated range of (V, R) conditions.

Based on the observation of the optical microscopy, the onset point of the chipping in terms of the feed velocity V has been determined at varying rates of the spindle rotation R_s, and the results are shown in Fig. 4 for samples S and A. The linear lines in Fig. 4 are the least square fits to each data set, which are the critical boundaries in the V–R space for the respective materials, from and above which the chipping takes place and below which no chipping transpires. Fig. 4 confirms that there exists a critical boundary in the V–R space for each material. For the investigated samples, the critical boundary line turns out to be roughly linear in the investigated range of the spindle rotation rate R (10k–40k rpm). The position and slope of the boundary line turn out to be material dependent.

At 10k–30k rpm of R, the drilling machinability of sample A can be said to be superior to that of sample S, while more or less similar at 40 rpm, from the viewpoint of the onset of chipping itself, regardless of the mode of chipping (LC or UC). The relative drilling machinability of sample S compared to sample A may be quantified based on the onset condition of chipping at a given rpm. The fitted boundary line equations (i.e. the least-square-fitted linear equations for the cases of the samples A and B) may serve the quantified drilling machinability of machinable ceramic materials; the machinability of versatile machinable ceramics can be reported or compared on a quantitative base by the determined equation of the critical boundary in the V–R space.

The physical origin for the existence of such a critical boundary in the V–R space may be conceived by considering the competition between the rate of drill penetration (RDP) and the rate of material removal (RMR). The rate of drill penetration (RDP) is given by

$$RDP = AV = \frac{\pi D^2}{4} f R$$

where A (m^2) is the cross-sectional area of the drill and D (m) is the diameter of the drill, and where R and f are the same as before. At a given rate of the spindle rotation R, if the feed velocity $V(=fR)$ is sufficiently small, all of the material debris formed by the drilling operation will be removed suitably from the hole during the drilling operation, and thus, the *RMR* will be the same as the *RDP*. However, as V keeps increasing at a given R, the *RDP* may exceed the rate of debris removal (*RMR*), which may pressurize the hole being drilled. Such pressure may cause chipping in the rear side of the specimen at the moment when the drilling is almost completed (i.e. when the residual thickness of material ahead of the drill tip is very thin). Thus, a critical V at a given R may exist. The connection of such critical V values causing chipping at the extended R range may form the critical boundary in the V–R space. In this sense, the position and shape (linear or non-linear) of the critical boundary line in the V–R space may be dependent on not only the material types of the specimen as mentioned (which controls the endurance of the build-up pressure) but also the geometry of the drills (including diameter, cutting edge length and angle, web thickness and chisel wedge width), since the geometry controls the rate of material removal. The position and shape of the critical boundary line in the V–R space may be a subject of study in a wide range of R for various machinable ceramic materials.

5. Conclusion

Two types of the BN-containing machinable ceramic samples were fabricated and machined to 0.4 mm thick plates to test the drilling machinability by using a 100 μm-diameter drill at the varying feed speed V (mm/min) at a given rate of the spindle rotation R (10k–40k rpm). At each investigated R (rpm), there exists a critical V above which the chipping takes place and below which there is no chipping, based on the optical microscopy observation of the holes at the rear side of the plates. The connection of the critical V determined at other R_s yields a critical boundary in the V–R space. For the cases of the investigated specimens, the critical boundaries are shown to be roughly linear in the investigated range of R, while the position and shape (linear or non-linear) of the boundary may be dependent on material types as well as on the geometry of the drills. The fitted equation of the critical boundary may serve the quantified drilling machinability of machinable ceramic materials.

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