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Analysis of Size Effect of Nano Scale Machining Based on Normal Stress and Indentation Theories

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수직응력과 압입이론에 기반한 나노스케일 기계가공에서의 크기효과 분석

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ABSTRACT

Recently nano meter size pattern (sub-micro scale) can be machined mechanically using a diamond tool. Many studies have found a ‘size effect’ which referred to a specific cutting energy increase with the decrease in the uncut chip thickness at micro scale machining. A new analysis method was suggested in order to observe ‘size effect’ in nano scale machining and to verify the cause of the ‘size effect’ in this study. The diamond tool was indented to a vertical depth of 1,000nm depth in order to simplify the stress state and the normal force was measured continuously. The tip rounding was measured quantitatively by AFM. Based on the measurements and theoretical analysis, it was verified that the main cause of the ‘size effect’ in nano scale machining is geometrically necessary dislocations, one of the intrinsic material characteristics. st before tool failure.

Key Words : Nano Scale Machining(나노스케일가공), Size Effect(크기효과), Tip Rounding(공구마모), Intrinsic Material Characteristics(재료내부특성), Indentation(압입)

1. Introduction

Machinable pattern size when planing and shaping is getting smaller and smaller by virtue of the incredible progress of the process technology and system technology[1,2]. Nowadays nano meter size patterns (sub-micro scale) which previously could be machined only by lithography and etching can be machined mechanically using a diamond tool. Since mechanical machining technology such as planing

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and shaping is the cheapest and most efficient machining method for mass-production, the ability to mechanically machine nano meter patterns on a metal mold is a very powerful technology for industrial fields. However, new parameters should be considered for nano scale machining; the representative parameters are tip rounding and intrinsic material characteristics. Since conventional mechanical machining deals with macro-scale shapes, the diamond tool tip is assumed to be ideally sharp. However, the diamond tool tip is not sharp but rather is round as shown in Fig. 1, and its radius has a range of several tens of nanometers to several micrometers[3], which is similar to or larger than the pattern size in nano meter machining. Intrinsic material characteristics such as dislocation and grain boundary are known to play important roles in the nano scale. This study investigated and analyzed quantitatively how tip rounding and the intrinsic material characteristics affect sub-micro scale machining.

2. Analysis methods

2.1 Conventional analysis

Many studies of micro scale machining have dealt with the size effect[3-5]. Many researchers have observed that the specific cutting energy (p_s) defined in Eq. (1) increases with a decrease in the uncut chip thickness; the phenomenon has been referred to the ‘size effect’. The specific cutting energy is defined as the energy required to remove a unit volume in the cutting direction; this definition also includes the resistant stress against cutting of machined material. Thus, an increase in the resistance from a machined material gets larger the cutting depth decreases. The theories that have beenused to explain the ‘size effect’ can be divided into two categories. One deals with the tip rounding[3,4].

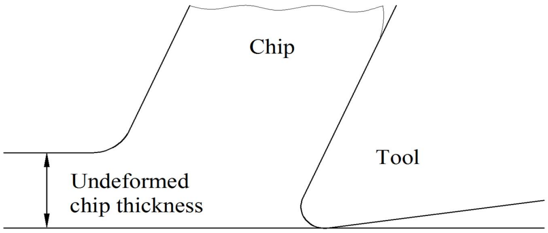

Fig. 1 Cutting with a blunt tip

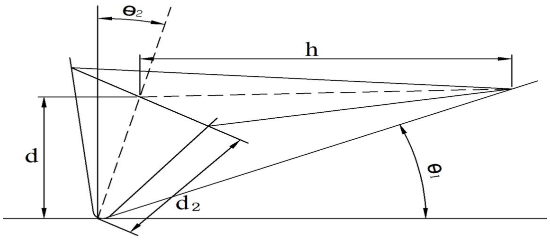

Fig. 2 A schematic diagram of cutting tool

Since the plowing force (F_p) is constant during micro scale machining, the ratio of the plowing force to the total cutting force becomes larger as the cutting depth becomes smaller. This makes the resistance be larger. However, this theory does not consider the intrinsic material characteristics which must be considered at the nano scale. Moreover, the stress state is complex and is hard to measure because only the sum of the forces can be measured.

$$p_s = P_m/Z_w = F_c/A_c \quad (1)$$

(P_m : rate of energy consumption during machining, Z_w : metal removal rate, F_c : cutting force, A_c : cross-sectional area of the uncut chip)

The other theory to deal with this phenomenon is material strengthening. Shaw explained the ‘size effect’ as arising from dislocations, which general metals contain inevitably[6]. Dislocation theory assumes that metals are deformed by defects inside the metals; thus, the shear strengths of the metals are much lower than the theoretical values.

Dislocations are representative of defects. Shaw derived an equation about shear strength and the uncut chip thickness based on dislocation theory. This equation indicated that the shear strength was proportional to the inverse number of the uncut chip thickness. Therefore, larger stress is required to cut metals at smaller cutting depths. Our research considered the intrinsic material characteristics; however, the ‘size effect’ can be explained using this theory even if the diamond tool tip is ideally sharp which is impossible in nano scale machining.

2.2 New analysis

As described above, several points needed to be considered simultaneously in order to analyze the ‘size effect’ in nano scale machining: (1) simplifying the stress state, (2) measuring the diamond tool tip rounding, (3) considering the intrinsic material characteristics, and (4) doing experiments at the nano scale. Therefore, a new experiment and analysis is suggested in this study. A diamond tool is indented on a metal mold only in the normal direction, in order to simplify the stress state, which is uniaxial. The maximum indenting depth is set at 1,000nm for the nano scale experiment; the normal force and the indenting depth are measured continuously. The normal force can be regarded as the cutting force. The detailed shape of the diamond tool tip is measured directly by AFM (Atomic Force Microscope); the exact cross-sectional area including tip rounding can be calculated. The normal stress derived from the measured force and the calculated cross-sectional area, is the same as the specific cutting energy. The normal stress should be constant regardless of the indented depth if the diamond tool tip is ideally sharp and if the material is uniform[7]. If the normal stress is not constant even when using an ideal cross-sectional area, this means that the intrinsic material characteristics are responsible for the change. Moreover, the comparison of the two types of normal stress from the ideal cross-sectional area and the measured cross-sectional area will show the effects of the tip rounding on the ‘size effect’. This new analysis seems to be similar to a previous study of Dinesh et al.[5] due to using indentation method. However, Dinesh focused on a theoretical analysis of indentation methods for analyzing the intrinsic material characteristics and did not consider the tip rounding. This new analysis can consider the tip rounding and the intrinsic material characteristics simultaneously based on the experimental results.

3. Experimental procedures

The suggested indenting experiment was performed using an ultra-fine planer (UVM-450C, Toshiba Machine) and a single-crystal diamond tool having 90 degrees tool angle which were used for the nano scale machining. The diamond tool was indented to 1,000nm depth into a metal mold of 64 brass (Muntz alloy) with 100mm/min velocity as shown in Fig. 2. This velocity was much slower than the velocity used in Nakayama’s research[3], so that there were no thermal or strain rate effects in this experiment. The normal force was measured continuously using a dynamometer (MiniDyn 9256C, Kistler). After removing the diamond tool from the metal mold, the tip shape of the diamond tool was measured by AFM (XE-100, Park Systems). The measured AFM data was converted to values of cross-sectional area using MATLAB software. Finally, the normal stress was calculated from an initial depth and to 1,000nm using the measured normal force and the converted cross-sectional area.

4. Results & Discussion

Measured normal force below 100nm depth was lower than the threshold value of the utilized dynamometer. Small oscillation was also observed at low depth because the ultra-fine planer and the dynamometer were optimized using micro scale machining. Therefore, we used the measured normal force beyond depths of 100nm and fit the data into the second order polynomial function. It is known that the normal force generally follows the second order polynomial function in the case of nanoindentation[8]. The adjustment R-square value of the fitted curve was 0.950, which means that the fitted curve can represent the measured normal force curve.

An AFM image of the diamond tool, reconstructed using MATLAB software, is shown in Fig. 3. The raw AFM data was converted to ASCII format, and the origin was reset on the tip point of the diamond tool. The two angles (θ_1 and θ_2) in Fig. 2 were 1.4 degrees and 1.6 degrees, respectively. The cross-sectional area of the diamond tool was derived from the tool shape for every 1nm of depth as shown in Fig. 4. The ideal cross-sectional area of the diamond tool was also calculated using Eq. (2).

$$Ideal\ area = \left(d^2/\cos\theta_2\right)\left(\tan\left(90-\theta_1\right)-\tan\theta_2\right) \qquad (2)$$

Finally, the normal stress was obtained from the measured normal force and the real cross-sectional area, as shown in Fig. 5. The normal stress was about 1,200MPa at 100nm depth, and was decreased to about 450MPa at 1,000nm depth. A rapid decrease was observed at very low depths; the degree of decrease became lower with increases of the depth. The normal stress, based on the ideal cross-sectional area, was also calculated, with results as shown in Fig. 5, in order to verify that this phenomenon was originated from the tip rounding. Ideal area means that the diamond tool tip is ideally sharp, so that the area at the end point of the diamond tool tip should be zero. The normal stress should approach infinity at very low depths. Moreover, considering the tip rounding, the ideal area is always smaller than the area measured by AFM, as shown in Fig. 6, and consequently the normal stress from the ideal area is always larger.

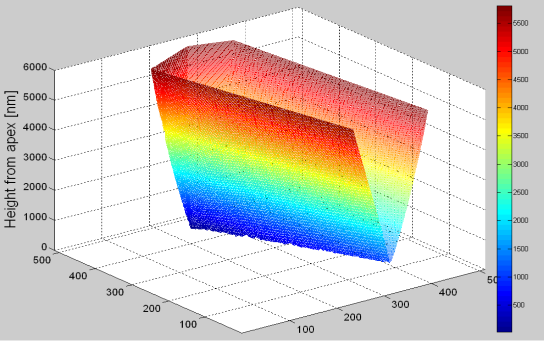

Fig. 3 Tip shape measured by AFM and converted by MATLAB

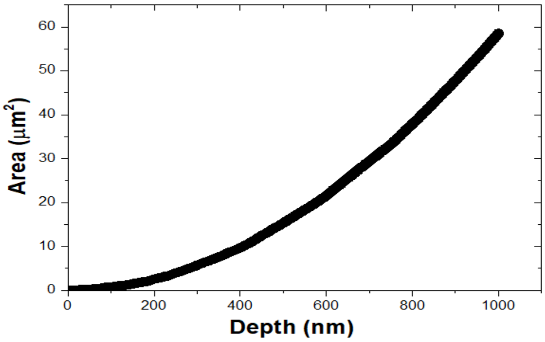

Fig. 4 The cross-sectional area of the diamond tool

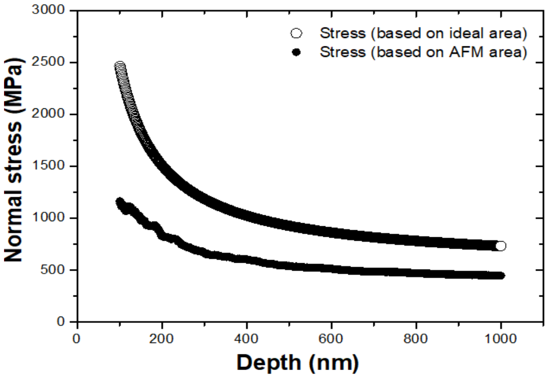

Fig. 5 Two types of normal stress calculated from the real cross-sectional area and the ideal cross-sectional area

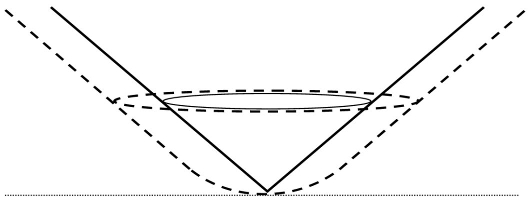

Fig. 6 A schematic diagram of two types of cross-sectional areas of an ideally sharp tip (straight line) and a blunt tip (dashed line)

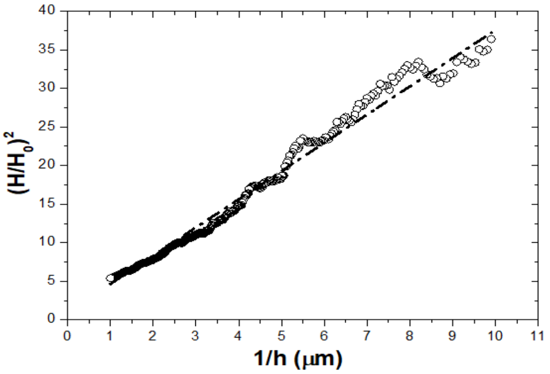

Fig. 7 A fitting graph of the normal stress according to the Nix-Gao model (points : normal stress, dashed line : linear fitted line)

Since the ‘size effect’ was observed to be more severe when the diamond tool shape was assumed to be ideally sharp, the conventional theory of the tip rounding and the plowing force were not able, alone, to explain the ‘size effect’ alone.

The normal stress in this study is similar to the indentation hardness from an instrumented indentation test. The round diamond tool can be assumed to be a spherical indenter. The representative strain (e) of the spherical indenter is expressed by Eq. (3)[9] or Eq. (4)[10]. The representative strain is found to decrease as the depth decreases, according to any two definitions and the representative stress is also found to decreases, too. This means that the tip rounding is characterized by a decrease in the normal stress as the depth decreases, which is contrary to the ‘size effect’. Therefore, the lower normal stress of the area measured by AFM can be explained by the tip rounding; however, the ‘size effect’ in nano scale machining cannot be explained in this way.

$$\epsilon = 0.2\sqrt{2Rd-d^2}/R \qquad (3)$$

$$\epsilon = 0.14\sqrt{2Rd-d^2}/(R-d) \qquad (4)$$

(R: the radius of the spherical indenter)

Previous studies have reported ‘indentation size effect’[13]. Several theories have been suggested to explain the ‘indentation size effect’; geometrically necessary dislocation (GND) theory is the most widely accepted. Unlike statistically stored dislocation (SSD), GNDs are required to accommodate inhomogeneous plastic deformations such as indentation and mechanical surface machining. While SSDs are independent of indentation depth, the density of GNDs gradually decreases as indentation depth increases, which results in an increase in the hardness with decreasing indentation depth, the so called indentation size effect (ISE). Nix and Gao introduced the indentation size effect model in[13]:

$$H/H_0 = \sqrt{1+(h^*/h)} \qquad (5)$$

where H is the measured hardness, H_0 is the macroscopic hardness, h* is the characteristic length of the ISE, and h is the indentation depth. According to the Nix-Gao model, we fit the normal stress in Fig. 5 as shown in Fig. 7. The graph of $(H/H_0)^2$ versus h was linear for any values of H_0, which means that the normal stress measured in this study follows the Nix-Gao model. When H_0=193 MPa, the linear curve has an intercept point at 0.994 on the y-axis. This value of H_0 is lower than the normal stress at 1,000nm, and can indicates the macroscopic hardness.

As described in this study, the ‘size effect’ in nano scale machining originates due to dislocation which is one of the intrinsic material characteristics. Based on the results of this study and on the spherical indentation theory, it is verified that tip rounding has a negative ‘size effect’. Therefore, the intrinsic material characteristics, especially dislocation, are the main reason for the ‘size effect’ in nano scale machining.

5. Conclusions

We have suggested a new method to measure and analyze the ‘size effect’ in nano scale machining. This method has several merits: (1) simplifying the stress state, (2) measuring the diamond tool tip rounding, (3) considering the intrinsic material characteristics, and (4) doing experiments at the nano scale. Based on this study, we have concluded:

1. The normal stress can be regarded as the specific cutting energy when a diamond tool is indented vertically.
2. A blunt tip should have larger cross-sectional area than an ideally sharp tip, which makes the normal stress of a blunt tip smaller than the normal stress of an ideally sharp tip. Moreover, representative stress increases with increases of depth in the case of a blunt tip. Therefore, tip rounding showed a negative ‘size effect’ in nano scale machining.
3. The measured normal stress followed the model of geometrically necessary dislocation theory of the indentation method. Therefore, geometrically necessary dislocation is the main reason for the ‘size effect’ in nano scale machining.

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