Effect of Contact Pressure Distribution on Surface Quality in Ice Bonded Abrasive Polishing

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Abstract

Ice Bonded Abrasive Polishing (IBAP) is a novel polishing method that employs ice to hold the abrasives firmly like bonded abrasive and becomes a slurry with the melting of ice during polishing thus behaving like loose abrasives. IBAP is capable of removing material as well as producing ultrafine finish on polished surfaces. This process does not need repeated dressing of tool since the abrasives, held by ice, become loose due to melting of ice during the operation. Due to this, fresh abrasives will come in contact with work surface continuously. The planarization defects significantly effect on quality of IBAP process. To address this issue, it is important to analyze the distribution of pressure on tool and work interface. In the present work, an attempt is made to develop a mechanistic model that can show up the pressure distribution on the tool work interface.

Keywords: Ultrafine finish, IBAP, Contact pressure

1. INTRODUCTION

Ultrafine finished components find applications in various fields such as electronics, optics, bio-implants etc. which attracts the researcher attention to make the process better and better. Several types of polishing techniques are available such as abrasive flow polishing, ultrasonic polishing, elastic emission polishing, magneto-rheological polishing, chemical mechanical polishing etc. Broadly they can be categorized as bonded and loose abrasive polishing techniques. In bonded abrasive polishing process, material is removed uniformly because the abrasives are held tightly at their position by the bonding agent. But, the resulting surface will contain scratches yielding relatively poor finish on polished surface. Periodic dressing of tool is essential in fixed abrasive polishing. In case of loose abrasive polishing techniques, ultrafine surface finish can be obtained without any loading. Due to random distribution of abrasives in loose abrasive polishing, the material removal is not uniform. In contrast to this, Ice Bonded Abrasive Polishing (IBAP) is a novel technique, in which ice will hold the abrasives like bonded abrasive tool. Upon its melting, slurry of water and abrasives, loose abrasives, participate in polishing. Due to this, fresh abrasives will come in contact with work surface continuously. IBAP is capable of removing material as well as producing ultrafine finish [1]. In order to get control over the process, proper understanding of the mechanism is required, which is possible through mechanistic modeling. Although many experimental works have been done in IBAP, no model has been developed till now. Hence, this paper aims to develop a preliminary model of IBAP.

As very few literatures are available for IBAP. Kinematics of IBAP is quite similar to CMP process, hence detailed study of CMP mechanism will be helpful for developing the model. Many researchers attempted to model the CMP process considering different theories. These models can be categorized in to three types. First attempt was taken by considering pure fluid mechanics. In these types of models, it is assumed that the down load is completely supported by a continuous slurry film separating the wafer and pad. The wafer surface material is removed by the tangential stress of flowing slurry [2]. But afterwards it was found that slurry can help only in distributing the abrasives over the interface and it cannot undertake the load. In the second attempt contact mechanics was taken in to consideration, where it was assumed that material removal is happening through abrasion in solid-solid contact and elastic contact theory was adopted to model the process. These models were widely accepted as the model outcomes were found satisfactory and resembled close values to the experimental observations [3]. In the third attempt plastic deformation was considered [4], where it was assumed that the interaction between pad-wafer results plastic deformation and the interaction between Pad-abrasive results elastic deformation. These models also focus on effect of abrasive particle distribution and pad property. In the present paper contact mechanics approach has been considered.

Ultrafine finishing processes are highly time consuming, pose planarization and structural changes on polished surfaces, and are of serious concern for manufacturing researchers. Among the various parameters that influence the process outcomes, planarization defects significantly affect the quality of IBAP process. To address this issue, it is important to analyze the distribution of pressure on tool and work interface. The process involves three prominent mechanisms. Initially the workpiece comes in contact with first layer of ice. Hence contact will be between ice and workpiece. Simultaneously the fixed abrasives come out as the first ice layer melts due to the frictional heat generated. Hence the abrasives and workpiece come in contact with each other, which is similar to the two-body interaction. Further rubbing of tool and workpiece lead to again melting of ice and slurry formation, which can be visualized as both 2 body (Fresh fixed abrasives and workpiece) and 3 body (free abrasive, workpiece and tool) interaction. In the current paper, interaction of ice and workpiece has been considered. An attempt has been made to model the contact pressure by considering Hertzian theory.

2. MODELING OF CONTACT PRESSURE

In IBAP process tool is prepared by freezing slurry layer by layer in order to get uniform distribution of abrasives throughout the tool thickness. Coolant is allowed to flow around the tool to maintain the tool temperature. A refrigeration unit has been

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employed to maintain the coolant temperature. The tool rotates around its own axis and a workpiece is placed at an offset from the tool axis, which also rotates around its own axis (Fig. 1(a)). Load is applied over the workpiece. Tool and workpiece rotation were differed from each other. Surface is generated due to relative motion between them.

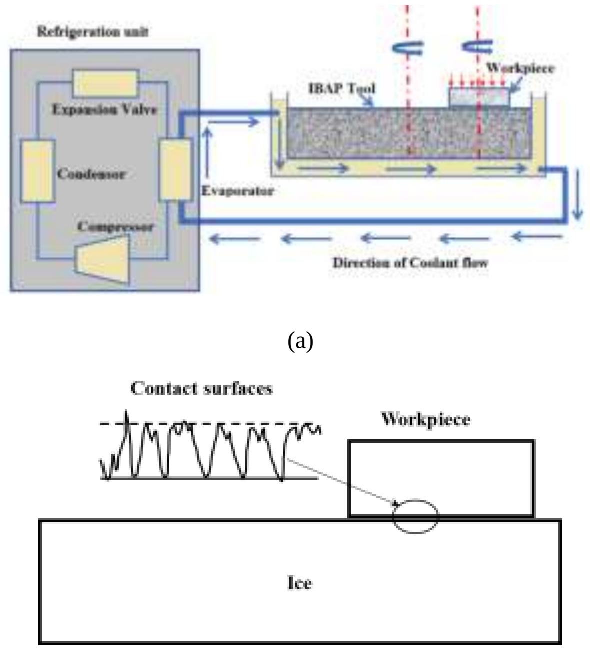

Fig. 1. (a) Schematic diagram of IBAP Process (b) Contact surfaces

Initially, the first ice layer will come in contact with workpiece. The contact can be considered as flat (ice) and rough surface (workpiece) interaction as shown in Fig.1 (b). Like Greenwood & Williamson model, asperity shape was assumed as hemispherical with same diameter and different height distribution [6]. When load is applied over the workpiece, deformation of workpiece asperities will initiate. According to the Archad assumption two cases can be happened, when two surface comes in contact with each other. In the first case the number of contact increases and area of contact will have linear relationship with force, meanwhile in the second case the number of contact remains same but the contact area of each asperity increases [5, 14]. In the present model, second case was adopted. For any axis-symmetric shape asperity, the contact area will be circular. As focus is on a small region, the asperity height distribution over the workpiece can be considered as Gaussian.

According to the Hertz theory, the real contact area of asperity will be

$$A_{re} = \pi R\delta \tag{1}$$

Where, R is the asperity radius and δ is the displacement caused due to loading (Fig. 4). The smooth surface (Ice) is at a distance d from the reference plane of rough surface as shown in figure 2. If h is the variable height of asperities, the asperities will come in contact with the smooth surface if $h \geq d$.

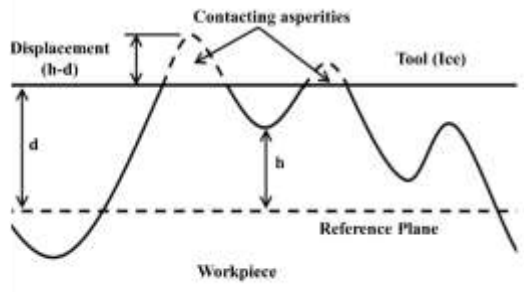

Fig.2. Workpiece asperity interaction with tool

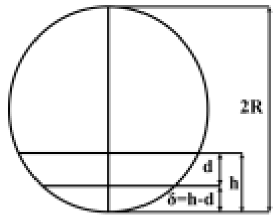

Fig.3. Geometry of spherical asperity indentation

Probability of contact between two surfaces:

$$P\ (h \geq d) = \int_d^\infty f(h)dh \tag{2}$$

Where $f(h) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{h^2}{2\sigma^2}}$, σ is the standard deviation. δ is the total displacement of asperities and can be expressed as *(h-d)*. If N is the total number of active asperity, Expected total real area of contact

$$A_{re} = \int_d^\infty \pi NR(h-d)f(h)dh \tag{3}$$

N can be obtained from the surface density of asperities on the workpiece.

$$N=\eta A$$

Where, η is the surface density and A is the apparent area of the workpiece. According to Hertz theory the contact pressure for single asperity is:

$$P = \frac{4E^* R^{\frac{1}{2}} \delta^{\frac{3}{2}}}{3} \tag{4}$$

The elastic and plastic contact depends on the displacement of asperities (Fig.3). The critical displacement of asperities for elastic to plastic transition can be obtained in terms of material properties of both surfaces.

$$\delta_{max} = \frac{\pi R H_w}{E^*} \tag{5}$$

Where H_w is the Brinell hardness of workpiece and E^* is the combined Young's modulus, which can be expressed as

$$\frac{1}{E^*} = \frac{1-\upsilon_w^2}{E_w} + \frac{1-\upsilon_t^2}{E_t}$$

Where, υ_w = Poisson's ratio of workpiece, υ_t= Poisson's ratio of tool, E_w=Young's modulus of workpiece, E_t=Young's modulus of tool.

If the displacement is below δ_{max} elastic deformation of asperity will result. Hence contact pressure for elastic deformation can be expressed as:

$$P = \frac{4E^{*}NR^{\frac{1}{2}}}{3}\int_{d}^{\delta_{max}}(h-d)^{\frac{3}{2}}f(h)dh \quad (6)$$

If the displacement exceeds δ_{max}, then plastic deformation of the asperities takes place. In real practice height asperity cannot be considered up to infinite. Area under the curve between six sigma ranges covers 99.73% of height variation. The normal distribution curve rapidly tends to zero after three times of its standard deviation on both positive and negative sides. Hence if the upper limit will be taken as 3σ, that will not affect the contact pressure value significantly. Hence the contact pressure for plastic deformation can be expressed as:

$$P = \frac{4E^{*}NR^{\frac{1}{2}}}{3}\int_{\delta_{max}}^{3\sigma}(h-d)^{\frac{3}{2}}f(h)dh \quad (7)$$

Surface finish will depend on the number of asperity gone through plastic deformation [15]. Which can be obtained as the ratio of total plastic deformation and number active grains. Hence surface finish of workpiece can be expressed as

$$R_a = \frac{N}{N_1}\int_{d+\delta_{max}}^{3\sigma}(h-d)f(h)dh \quad (8)$$

Where, N_1 is number of active grains for plastic deformation

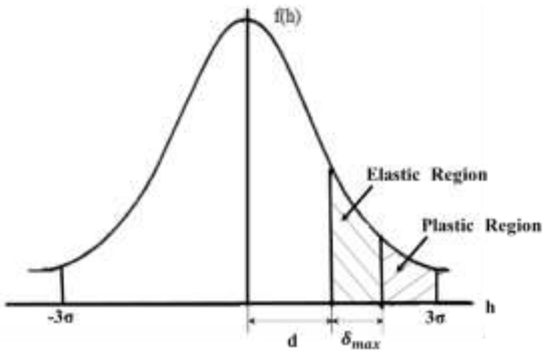

Fig.4. Gaussian distribution of asperity heights

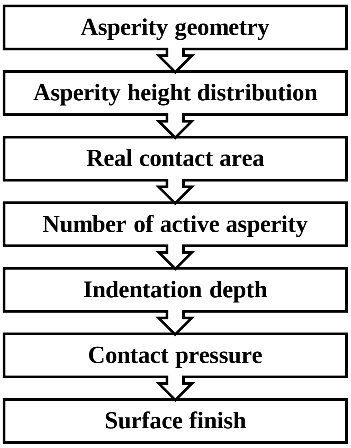

Fig. 5. Methodology for model development

3. EXPERIMENTAL DETAILS

In order to validate the above model, an experiment was carried out on Ti6Al4V. A 20 mm diameter and 15 mm thick cylindrical workpiece is prepared. For initial surface preparation, it is rubbed with emery sheets of different grit sizes (340, 400, 600, 800, and 1000) and finally it was polished in a polishing machine which was set at 300 rpm and 9 micron diamond slurry was used. Initial surface profile was measured in 3D optical profilometer and found to have a surface roughness (Ra) value of 0.223 micron. (Fig.6.)

First step for IBAP process is to prepare tool. Distilled water was taken and frozen layer by layer. Rotational speeds for tool and workpiece were selected 150 rev/min and 200 rev/min respectively. Workpiece was placed at an eccentricity of 65 mm from the tool axis. After polishing, the surface roughness was found 0.199 micron. The surface profile is shown in figure 7.

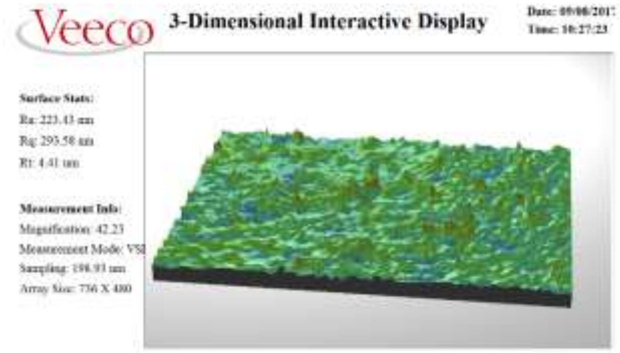

Fig. 6. Initial surface profile of workpiece

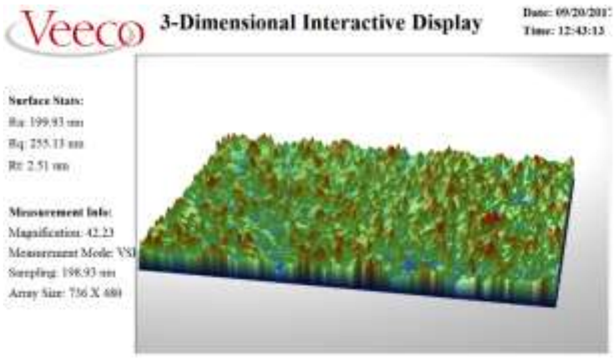

Fig. 7. Surface profile of workpiece after polishing

Table 1: Material properties of Ti6Al4V and ice.

Sl. no.	Material property	Values
1	Poisson's ratio workpiece	0.342
2	Poisson's ratio of ice	0.31
3	Young's modulus of workpiece	113 GPa
4	Young's modulus of ice	10 GPa
5	Hardness of workpiece	334

4. RESULTS AND DISCUSSIONS

The material properties used in the model is tabulated in Table 1. The corresponding input data for the model was taken by analyzing the initial surface profile of the workpiece. The optical path difference (OPD) images captured in 3D profile-meter were analyzed using Vision software. Surface density and standard deviation parameters were obtained by extracting data from them.

The proposed model was simulated using MATLAB. The real contact area and contact pressures were calculated. As hardness of ice is less as compared to hardness of Ti6Al4V, plastic deformation of workpiece will be negligible, which can be visualized by comparing the surface profile before and after polishing. The contact forces are plotted against the corresponding asperity height (Fig.8). The contact force increases nonlinearly with respect to height. It can be concluded that the pressure does not reach up to threshold limit which can generate plastic deformation of the asperity so, only elastic deformation is taking place.

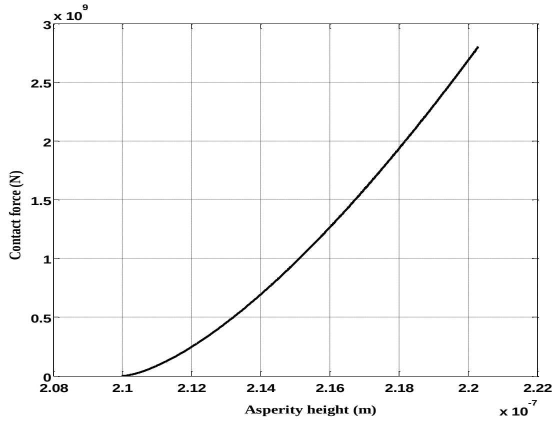

Fig. 8. Contact force variation with indentation depth

5. CONCLUSION

A preliminary attempt was made to model the IBAP process. Contact mechanics approach is implemented because of its satisfactory resembles with experimental observation. Three types of contact mechanism is assumed to be occurring during the process namely, ice workpiece contact, fixed abrasive workpiece contact and slurry workpiece contact. In the proposed model, ice workpiece contact was focused. Where the ice surface is taken as flat and workpiece surface is taken as rough having asperities distributed over the surface. Probabilistic approach was used for modelling. Hertzian theory was employed to calculate the real contact area and contact pressure. The contact pressure was found to be varying nonlinearly with asperity height. Polishing efficiency was found very less as ice hardness value is very less as compared to workpiece hardness. Hence, for ice workpiece contact elastic deformation is found dominant.

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