Int J Adv Manuf Technol (2016) 83:911–917
DOI 10.1007/s00170-015-7633-x

ORIGINAL ARTICLE

Modeling of edge tool influence functions for computer controlled optical surfacing process

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Received: 27 February 2015 / Accepted: 19 July 2015 / Published online: 2 August 2015

Abstract Computer-controlled optical surfacing provides superior optical fabrication performance with low-cost mass production over conventional method relying heavily on the skills of optician. However, there are still lots of technical issues to be resolved in computer-controlled optical surfacing, and edge effect has been regarded as one of the most challenging tasks for years due to the unpredictable behaviors of a polishing tool. As a polishing tool approaches the edge of the workpiece, the tool-workpiece contact area decreases and this in turn accompanies the tool-workpiece misfit and non-uniform pressure distribution. Thus, the edge effects should be taken into account in deterministic polishing technique. In this paper, we suggest new edge tool influence functions by modeling the velocity and pressure distribution of a polishing tool with eccentric rotation motion. Here, the finite element analysis was used to accurately predict the non-linear behaviors of a polishing tool at the edge. We verified our proposed method by comparisons with experimental results, and it shows considerable resemblance between them.

Keywords Edge effect · Edge tool influence functions · Computer controlled optical surfacing · Finite element analysis

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1 Introduction

Recently, the demands for large high-precision mirrors have been rapidly increasing in diverse applications such as lithography for nanoscale fabrication, spy satellite for military purpose, and telescope for observation of space. One of the most important factors affecting the performance of optical system such as light gathering power and resolving power is the diameter of the mirror, so the required mirror size for superior system performance has been steadily increasing. However, the technical barriers to enter into this field are still high, and it is considered as strategic technology critical to national security and military, so it makes more difficult to share knowledge and experiences between countries. Therefore, it is indispensable to invest in the research and development (R&D) to develop its own technology.

Various techniques are required for fabrication of large-scale optical mirrors, and especially computer-controlled optical surfacing (CCOS) technique [1–7] is regarded as the most important process. Because CCOS technique can provide the optimal solution for optical fabrication of mirrors in terms of mass production and lower production costs when compared to conventional method, which is relying heavily on the skill of the optician. Many research studies have been performed to achieve high convergence rates and high form accuracy during polishing process, but many obstacles still remain to be resolved. Especially, edge effect issues have been considered as one of the most challenging tasks due to the unpredictable behaviors of a polishing tool. As a polishing tool approaches the edge of the workpiece, the tool-workpiece contact area decreases, and subsequently, it accompanies the tool-workpiece misfit, non-uniform pressure distribution, and deformation of polishing tool. Thus, there have been many attempts to develop a predictive model of edge effects, which should be classified into mathematical model

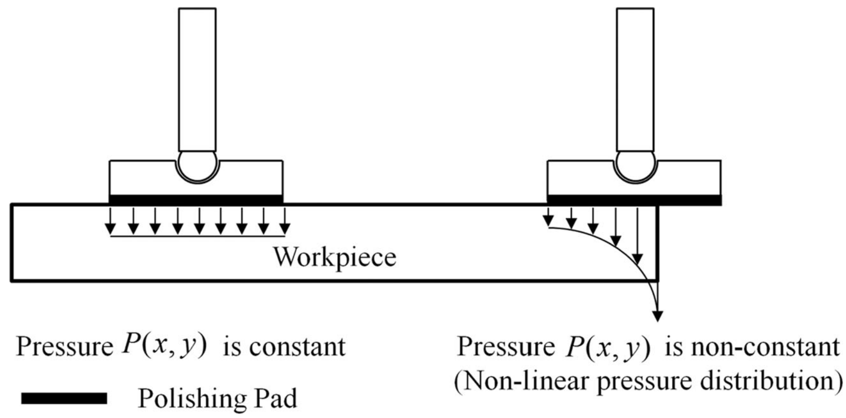

Fig. 1 The pressure distribution of a polishing tool when it overhangs the workpiece edge

based on mechanical equilibrium [8–10], numerical model derived from empirical data [11–13], and finite element analysis (FEA) model [14].

A theoretical pressure model based on the force and momentum equations was suggested by Wagner and Shannon [8], but a negative pressure distribution happens in this linear pressure model. To avoid this negative pressure, Luna-Aguilar et al. proposed a skin model for pressure distribution by subdividing the contact region into two zones of continuously growing pressure region and constant pressure region [9]. But this skin model was restricted to a square tool and square workpiece, so Cordero-Dávila et al. modified it to be applicable for a circular tool and circular workpiece [10]. Other models suggested by Kim et al. [11, 12] and Li et al. [13] predict the edge removal profile using measured data. Theses edge models are relatively accurate but difficult to apply to various tool conditions without experiments. Liu et al. proposed a new pressure model based on FEA by introducing a suitable soft layer to simulate the effect of abrasives during the polishing process [14], but this edge model is limited to the simple motion of a polishing tool.

Here, we modified the FEA model for accurate prediction of the pressure distribution of the polishing tool with eccentric rotation motion. The velocity distribution was obtained from the kinematic relation of the polishing tool motion. In this paper, we propose new edge tool influence functions (TIFs) being applicable under various tool motion conditions by modeling the pressure and velocity distributions of a polishing tool at the edge.

2 Modeling of edge effects

The equation of the material removal can be described by a linear relation of the pressure and velocity according to the Preston equation [15]

$$\Delta z = kP(x,y)V(x,y)\Delta T(x,y) \tag{1}$$

where Δz is the material removal from the workpiece, k the Preston coefficient related to polishing conditions other than the pressure and velocity such as material properties, tool condition, abrasives, and etc., ΔT the dwell time, P the pressure within the contact area of the tool and the workpiece, and V the relative velocity between the tool and the workpiece.

Edge effects happen near the edge of the workpiece. As shown in Fig. 1, the pressure distribution in the contact area of the polishing tool considerably increases when it overhangs

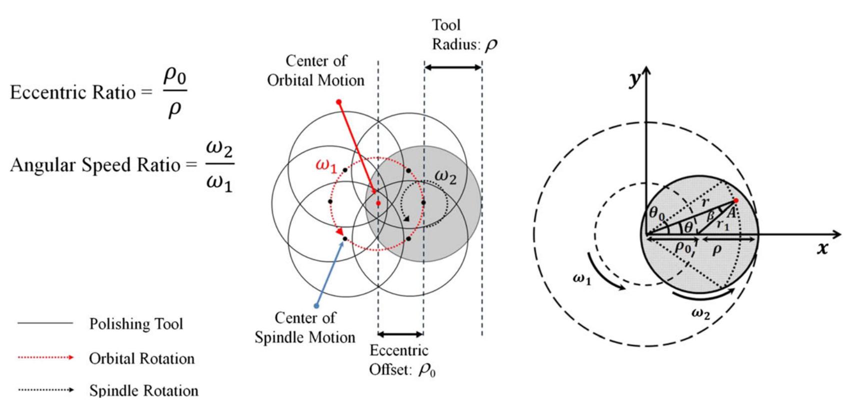

Fig. 2 Schematic diagram of the kinematic relation of the polishing tool with eccentric rotation motion (angular orbital speed=ω_1, angular spindle speed=ω_2)

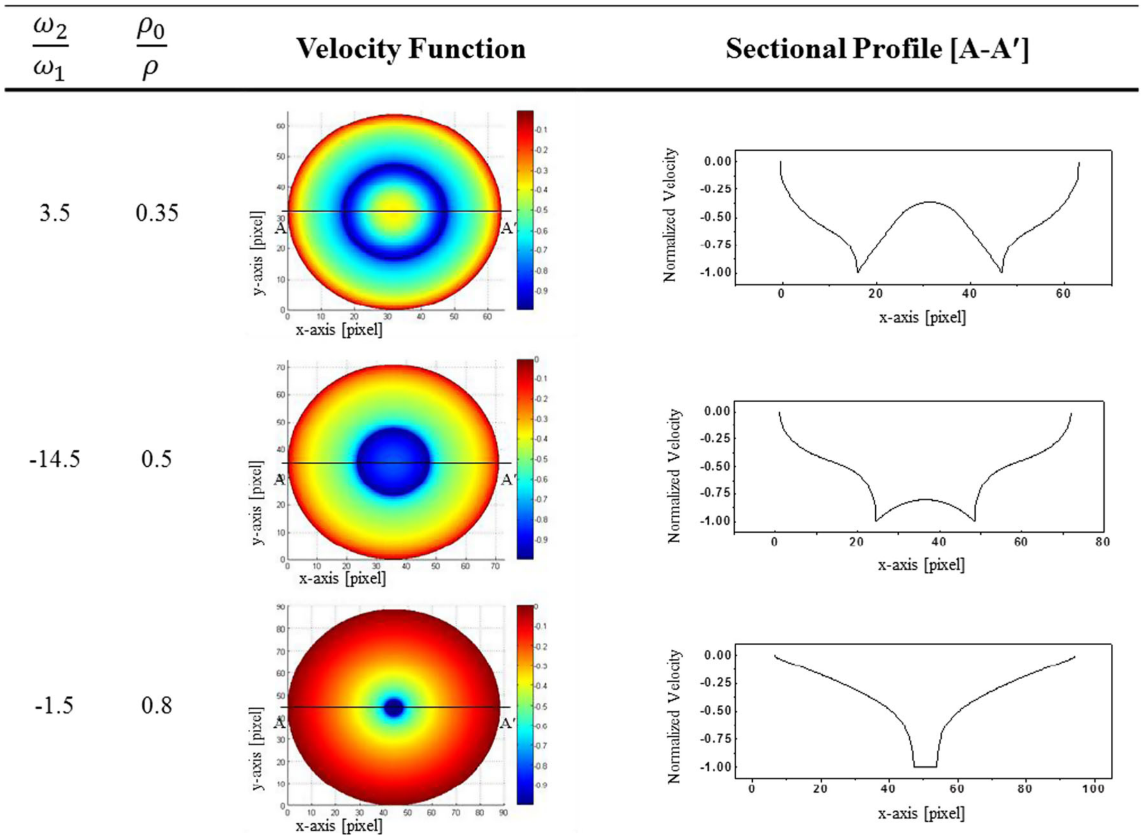

Fig. 3 The relative velocity distributions of a dual-rotation polishing tool according to different eccentric ratios and angular speed ratios

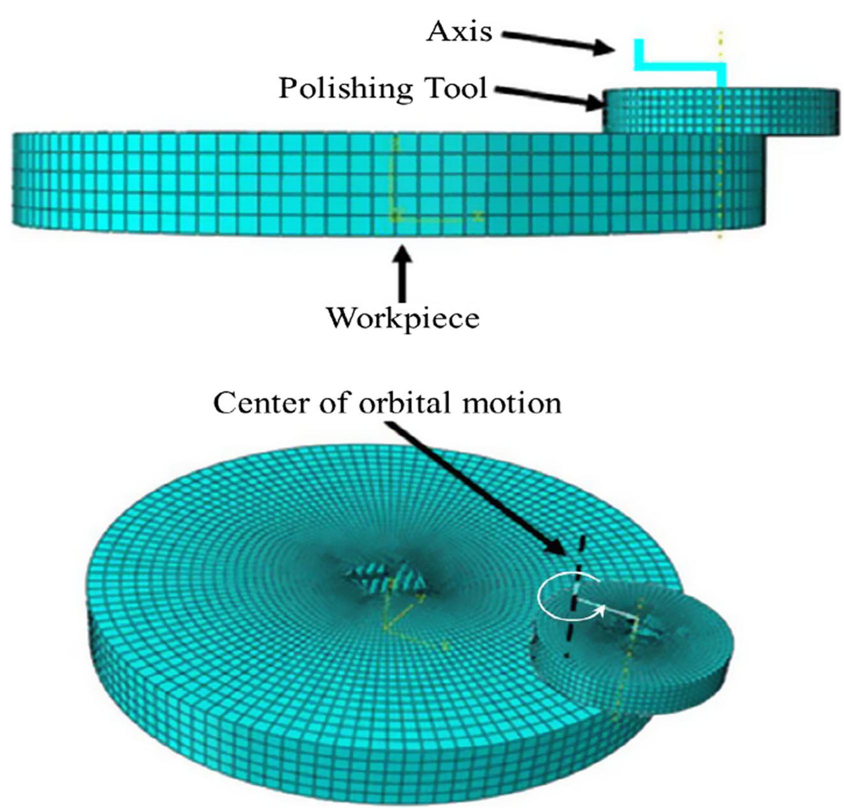

Fig. 4 The simplified FEA model for analysis of pressure distribution when the polishing tool overhangs the edge of the workpiece

Table 1 Material properties and specifications of mesh for the FEA

	Workpiece	Polishing tool	Axis
Material	ZERODUR	STEEL	STEEL
Density	2530 kg/m^3	7860 kg/m^3	7860 kg/m^3
Elastic modulus	91.0 Gpa	207.0 Gpa	207.0 Gpa
Poisson's ratio	0.24	0.3	0.3
Mesh type (in ABAQUS)	C3D8R	C3D8R	B31
Mesh size	2.5 mm (max)	0.8 mm (max)	0.1 mm (max)
Contact type	Surface-to-surface contact (workpiece and polishing tool)		
Constraint	Coupling type (kinematic, axis, and polishing tool)		

the workpiece, and this non-linear pressure distribution brings the intensive wear near the edge. For this reason, we cannot predict the exact amount and shape of material removal near the workpiece edge with conventional approaches, so edge effects have been regarded as one of the most critical issues in the figuring process for years.

In order to analyze the edge effects, we derive new edge TIFs based on the Preston equation. Here, we assume that the Preston coefficient k is a constant during polishing process, and the polishing tool head spins on a spindle axis with angular velocity ω_2 and this spindle rotates around an eccentric offset with angular velocity ω_1. Figure 2 shows the kinematic relation of the polishing tool with eccentric rotation motion, and the velocity distribution at A can be derived by the following equation [16, 17].

$$V(r) = C\int_{-\theta_o}^{\theta_o} \left[(r\omega_1)^2 + (r_1\omega_2)^2 - 2rr_1\omega_1\omega_2\cos\beta\right]^{\frac{1}{2}} d\theta$$

$$\text{where } r_1 = \left[r^2 + \rho_0{}^2 - 2r\rho_0 \cos\theta\right]^{\frac{1}{2}}, \cos\beta = \frac{r^2 + r_1^2 - \rho_0{}^2}{2rr_1}, \text{and } \theta_0 = \cos^{-1}\left(\frac{r^2 + \rho_0^2 - \rho^2}{2\rho_0}\right). \quad (2)$$

The relative velocity distribution of the polishing tool on the workpiece can be calculated using Eq. 2. Figure 3 shows the exemplary velocity distribution of a dual-rotation polishing tool according to different eccentric ratios and angular speed ratios. Throughout this process, we can model the velocity distribution of a polishing tool at various polishing conditions.

The pressure distribution of a polishing tool at the workpiece edge can be calculated using a commercial finite modeling software ABAQUS. Figure 4 shows our simplified model, and the material properties and specifications of mesh for the FEA are listed in Table 1. We used radial meshes with eight nodes and 22,500 for workpiece and 14,400 for polishing tool, respectively.

Figure 5 shows our constrained model of the polishing tool for the efficient FEA. As shown in Fig. 5a, the polishing pad acts as a buffer of the leaning phenomenon in the direction of movement of the polishing pad caused by frictional forces between the polishing pad and the workpiece, so it provides full contact with the workpiece during the polishing process.

In this simulation, we have simplified our FEA model by assuming that the polishing tool directly contacts the workpiece without the polishing pad, because it may cause some problems such as low reliability and time consuming analysis due to the complexity and specificity of the mechanical properties of the polishing pad. As shown in Fig. 5b, slight lifting phenomenon and abnormal pressure concentration happen in the movement direction of the polishing tool, so we applied new pressure constraint on the top of the tool in order to

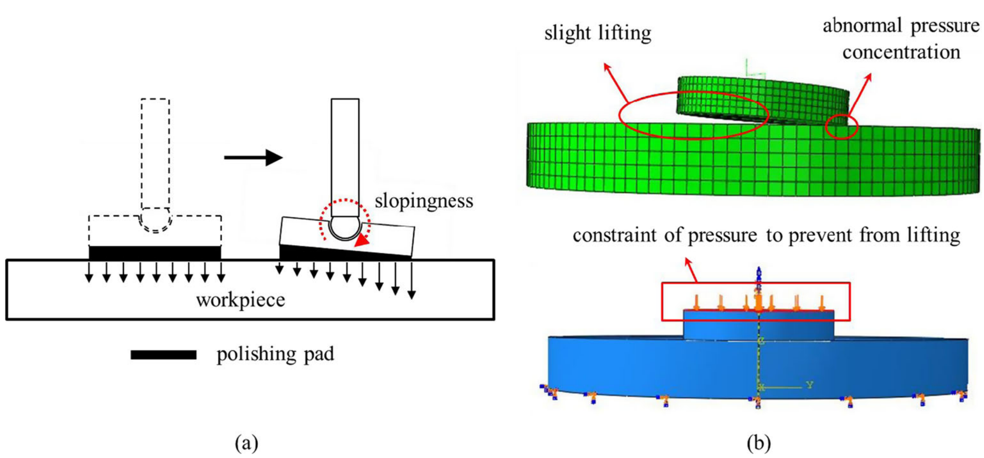

Fig. 5 **a** Schematic diagram of polishing tool when it is moving and **b** constrained model of polishing tool for the efficient FEA

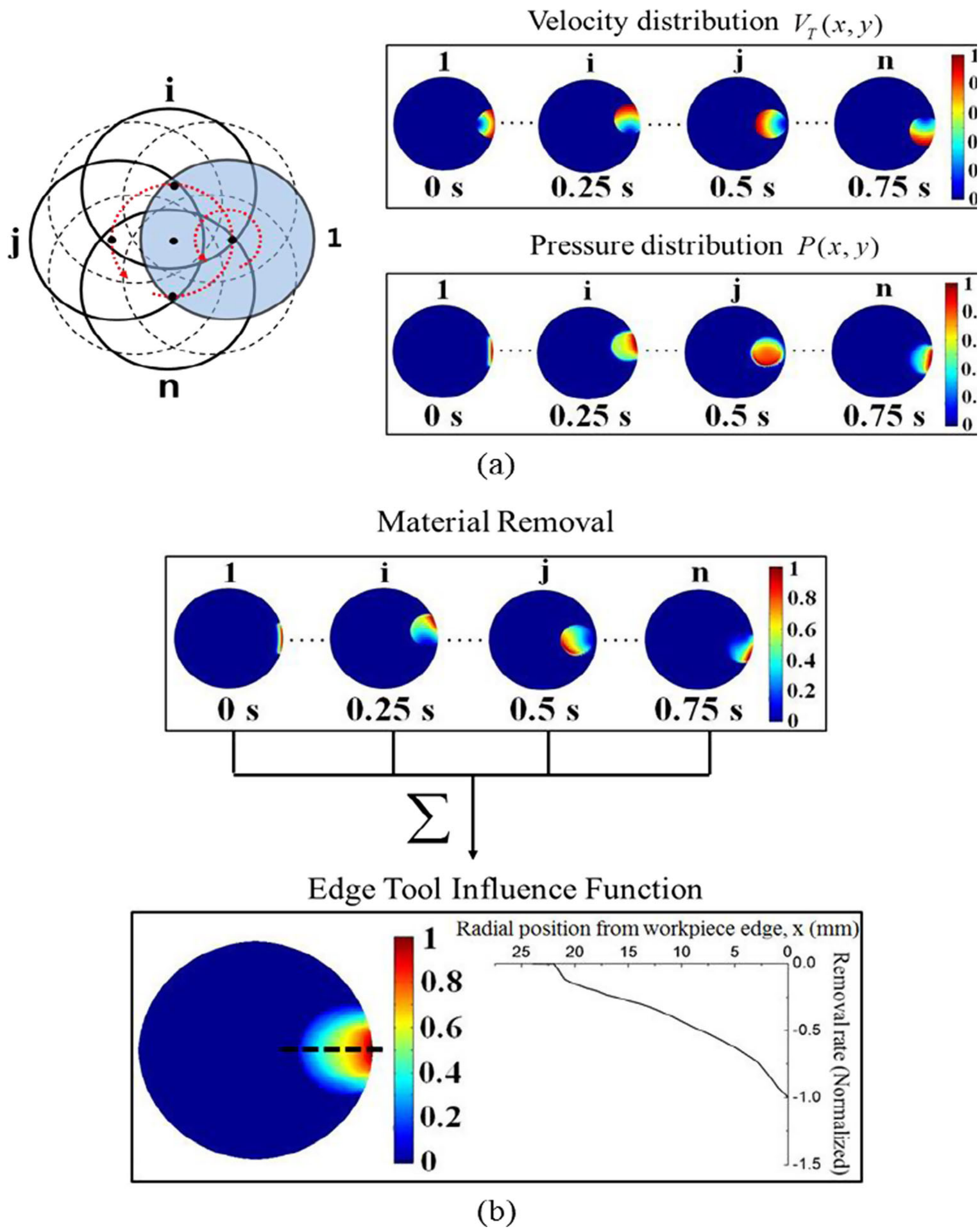

Fig. 6 **a** Normalized velocity distribution $V_T(x,y)$ and normalized pressure distribution $P(x,y)$ according to elapsed time during one polishing rotation and **b** their corresponding material removal at every 0.25 s and edge TIF

prevent from lifting in one side. Figure 6 describes our proposed method for modeling of the edge TIFs. As described above, the edge TIFs can be simulated by calculating the velocity and pressure distribution at the workpiece edge using the Preston equation. The velocity distribution $V_T(x,y)$ is derived by the kinematic relation of the polishing tool using Eq. 2, and the pressure distribution $P\ (x,y)$ is calculated using the FEA model to predict the non-linear behaviors at the edge of the workpiece. Here, we assume the polishing tool with 0.8 eccentric ratio orbits once per second. Figure 6a depicts the normalized velocity and pressure distributions at 0.25 s intervals, respectively, and Fig. 6b shows the edge TIF by multiplying the corresponding velocity and pressure distribution and summing them all during one polishing tool rotation.

We have verified our edge TIFs by comparing our simulations with experimental results under same conditions according to different overhang ratios. As shown in Fig. 7, our simulation results coincide well with the corresponding experimental results. But as the overhang ratio increases, experimental results show more excess wear at the edge resulting in a downturned edge. This inconsistency occurs because our edge model does not take into consideration the polishing tool being tilted to one side and contacted only at the edge during circular orbital tool motion as shown in Fig. 8. Further study will be needed to consider these factors in our edge TIF model to reduce errors in the simulation.

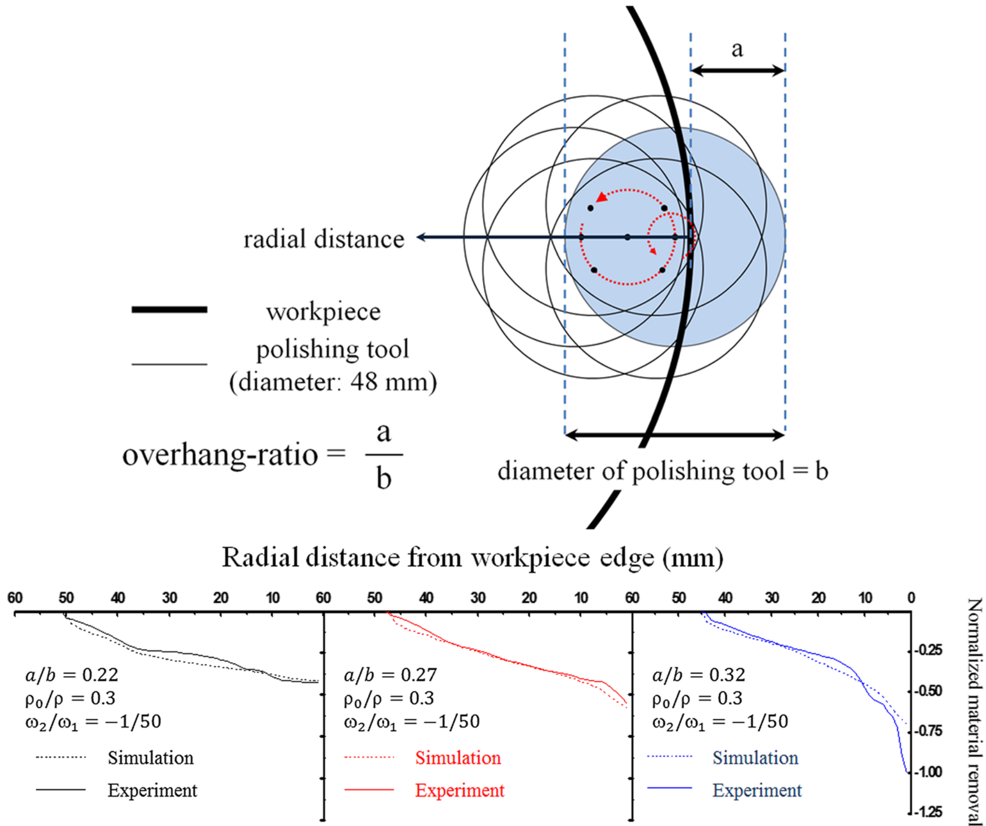

Fig. 7 Comparison between simulation and experimental results according to different overhang ratios (in this case, eccentric ratio=0.3, angular speed ratio=−1/50)

3 Conclusion

We have proposed and demonstrated a new edge removal model to describe the abnormal behaviors of a polishing tool when the tool overhangs the workpiece edge. The edge TIFs are obtained by calculating the velocity and pressure distribution of a polishing tool with eccentric rotation motion based on the Preston equation. The FEA method was used for accurate prediction of the non-linear behaviors of a polishing tool at the edge. Our edge TIF modeling was verified by comparing simulations with experimental results, and it shows a good agreement between them. We anticipate that this new edge TIFs will contribute on building up the efficient edge figuring process for large high-precision mirror fabrication.

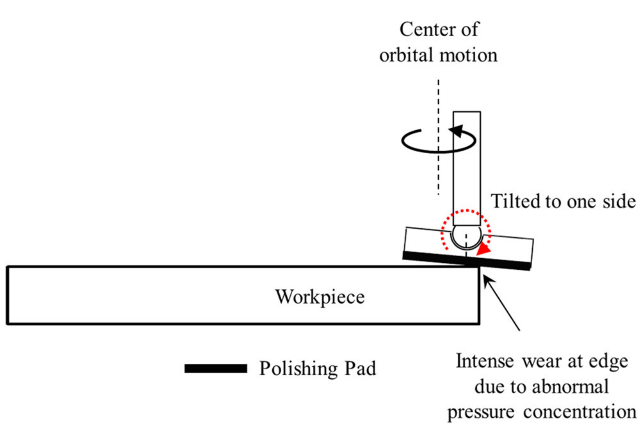

Fig. 8 The unpredictable intense wear at edge when the polishing tool is suddenly tilted to one side and contacted only at the edge

Compliance with ethical standards

Funding This study was funded by the UAV program in Korea.

Conflict of interest The authors declare that they have no conflict of interest.

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