Effect of Heat-Insulating Layer Thickness on Melting Rate of Ice Fixed Abrasives Polishing Pad

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Abstract: The formula of the thickness of the heat-insulating layer is deduced via heat transfer analysis, according to the principle of heat transfer in limited space. Polishing experiments are carried out using the same technological parameters. Compared with the polishing experimental results, the heat transfer model is proved to be correct. As validated by the experimental results, polyurethane heat-insulating layer can effectively improve the service life of the ice fixed abrasive pad and alleviate the melting rate in the polishing process to improve the polishing quality proposed. The heat transfer model provides theoretical basis for research of temperature field of ice fixed abrasive polishing.

Key words: ice fixed abrasive; heat-insulating layer; unsteady-state conduction

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0 Introduction

Ice fixed abrasive polishing technology is an integrated application used widely in mechanical engineering, especially in the precision and ultra-precision machining field, which is characterized by mixed cryogenic technology with fixed abrasive polishing technology. Mohan et al.[1] presented the efforts in the design, development and characterization of a novel method of ice bonded abrasive polishing process. Liu et al.[2] proposed an innovative way of abrasive free cryogenic polishing. Zuo et al.[3] investigated the ice fixed abrasive pad. Experimental results have proved that the finished surface residual stresses, micro-cracks, surface damages, etc. can be reduced by the improved technique during polishing[4-6]. It should be noted that the surface residual stresses have a strong effect on the fatigue life, crack resistance and corrosion resistance on the workpiece[7-10]. And it is easy to obtain ultra smooth surface in the atomic level. In order to increase the polishing life of ice fixed abrasive polishing pad, the melting rate should be decreased. It is necessary to place a heat-insulating layer on the top surface of the original cast iron base for reducing the heat exchange rate between the ice fixed abrasive polishing pad and the environment.

1 Heat Transfer in Cryogenic Polishing Process

In flat polishing, the ice fixed abrasive polishing is shown in Fig. 1. The polishing system consists of a pad carrier table, a workpiece holder and a cryogenic supplying system. Ice fixed abrasives rotates at a certain angular velocity, and the workpiece is pressed on the top of the ice fixed abrasives with the same angular velocity. During the polishing process, the fixed abrasive and workpiece fit together closely. Lots of point heat source will be generated due to the friction in the polishing area, which can be considered as a plane heat source of continuous distribution. The heat generated in the polishing area is transferred to workpiece and ice fixed abrasive. As the polishing

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is a complex process with frictional heating, it is simplified as contact heat transfer between the two surfaces in the present study.

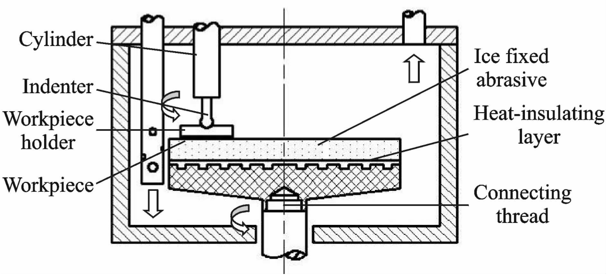


Fig. 1 Ice fixed abrasive polishing

1.1 Calculation of heat flux generated due to friction

Heat flux generated due to friction can be calculated as[11]

$$q_1 = \mu p v \tag{1}$$

where μ is the friction coefficient, p the pressure on the workpiece, and v the relative linear velocity between the ice pad and the workpiece (with the assumption of the same rotation speed ω of the ice pad and the workpiece, here, $v=\omega e$, e is the distance between the centre of ice pad and the workpiece, i. e. the eccentric distance). The average friction coefficient between the ice pad and the workpiece obtained by the experiments is $\mu=0.006\,2$, which was carried out by Sun et al. within a certain time and fixed spindle speed case[12].

1.2 Heat flux distribution coefficient

Heat flux generated due to friction will be transmitted to the ice pad and the workpiece, therefore, the distribution ratio should be determined. As presented in Ref. [11], it can be defined as

$$r = \left[1 + \left(\frac{k_2}{k_1}\right)\left(\frac{\kappa_1}{vl}\right)^{\frac{1}{2}}\right]^{-1} \tag{2}$$

where k_1 is the thermal conductivity of the ice, k_2 the thermal conductivity of the workpiece, κ_1 the thermal diffusivity of the ice, v the relative velocity, and l the diameter of the workpiece. So heat fluxes transmitted to the ice pad and the workpiece are rq and $(1-r)q$, respectively.

1.3 Convective heat transfer between ice pad and air

During the polishing process, in addition to heat flux generated due to the friction between the workpiece and the ice fixed abrasive, there are convective heat transfer in the surface of ice pad, heat transmission between the bottom of ice pad and cast iron base, as well as phase transformation heat transfer of the ice melting process. Due to the large thermal conductivity of cast iron, the bottom of ice pad always melts first. This phenomenon will cause the ice pad to shed and break, thus resulting in a significant reduction of the service life of the ice pad. Therefore, it is necessary to place a heat-insulating layer on the top surface of cast iron base to decrease the melting rate of the ice.

During polishing process, the ice pad is in a rotational state. Assuming the forced convection heat transfer between the ice pad surface and the air is in the limited space without phase transformation. As presented in Ref. [13], the convective heat transfer coefficient can be calculated as

$$h = \frac{Nu_r \lambda}{r} \tag{3}$$

For laminar flow

$$Nu_r = \frac{0.585 Re_r^{0.5}}{0.6/Pr + 0.95/Pr^{1/3}} \tag{4a}$$

$Re_r \leqslant 2.4\times10^5$, any Prandtl number

For turbulent flow

$$Nu_r = 0.021 Re_r^{0.8} Pr^{1/3} \tag{4b}$$

$Re_r \geqslant 2.4\times10^5$, $Pr > 0.5$

$$Re_r = \frac{\Omega r^2}{v} \tag{5}$$

where Nu_r is the partial Nusselt number of radius r, λ the thermal conductivity of air, r the radius of ice pad, Re_r the rotate Reynolds number, Pr the Prandtl number of air, Ω the rotational angular velocity, and v the kinematic viscosity of air.

1.4 Heat transfer between ice pad and heat-insulating layer

To increase the life of ice fixed abrasive polishing pad and reduce the melting rate during the polishing process, a polyurethane heat-insulating layer is placed on the top surface of the original cast iron base to reduce the heat exchange between the ice fixed abrasive polishing pad and the external environment. Assuming that the heat transfer is a one-dimensional steady-state heat transmission among the bottom surface of the ice pad, heat-insulating layer and the cast iron base. As presented in Ref. [14], the heat flux can be expressed as

$$q_2 = \frac{t_1 - t_4}{\dfrac{\delta_1}{\lambda_1} + \dfrac{\delta_2}{\lambda_2} + \dfrac{\delta_3}{\lambda_3}} \tag{6}$$

where λ_1, λ_2, λ_3 are the thermal conductivities of ice, heat-insulating layer, and cast iron base, respectively; and δ_1, δ_2, δ_3 the thicknesses of ice, heat-insulating layer, and cast iron base, respectively.

The thickness of the heat-insulating layer has a certain effect on the melting rate of ice fixed abrasive polishing pad. The existence of heat-insulating layer can make the ice melt more gently. If the thickness of the heat-insulating layer is more than 23.1 mm, the life of ice pad will decrease. It can be attributed to the ice pad gripping instability caused by high heat-insulating layer, which results in a phenomenon called the "Shoveling ice" that can accelerate the melting rate[15].

2 Thickness Determination of Heat-Insulating Layer

In the ice fixed abrasives polishing experiments, the particular experimental conditions are assumed as: workpiece diameter $l = 2$ inch, eccentricity $e = 75$ mm, polishing pressure $p = 0.025$ MPa, spindle speed $\omega = 300$ r/min, environment temperature $t_1 = 283$ K, and ice pad initial temperature $t_4 = 263$ K.

2.1 Calculation of frictional heat flow

The parameter q_1 can be computed according to Eq. (1) as

$$q_1 = \mu p v = 0.006\,2 \times 0.025 \times 10^6 \times 300 \times \frac{2\pi}{60} \times 75 \times 10^{-3} = 365.21\ \mathrm{W/m^2}$$

With reference to Eq. (2)

$$r = \left[1 + \left(\frac{k_2}{k_1}\right)\left(\frac{\kappa_1}{vl}\right)^{\frac{1}{2}}\right]^{-1} = \left[1 + \left(\frac{0.21}{2.22}\right) \times \left(\frac{\dfrac{2.22}{913 \times 2.1 \times 10^3}}{300 \times \dfrac{2\pi}{60} \times 75 \times 10^{-3} \times 50.8 \times 10^{-3}}\right)^{\frac{1}{2}}\right]^{-1} = 0.999\,7$$

If $k_2 \ll k_1$ or $\dfrac{Vl}{\kappa_1} \gg 1$, it means all the heat conducting into material 1 (ice pad) can be expressed as: $rq_1 = 365.1\ \mathrm{W/m^2}$.

2.2 Calculation of air convection

Firstly, the rotate Reynolds number should be calculated to ensure the choice of Eq. (4). With consideration of Eq. (5)

$$Re_r = \frac{\Omega r^2}{\nu} = \frac{2\pi \times 300/60 \times (100.4 \times 10^{-3})^2}{13.28 \times 10^{-6}} = 2.38 \times 10^4 < 2.4 \times 10^5$$

It can be clearly seen that the ice pad is in a laminar flow state. Therefore, Eq. (4a) is used.

$$Nu_r = \frac{0.585 Re_r^{0.5}}{0.6/Pr + 0.95/Pr^{1/3}} = \frac{0.585 \times (2.38 \times 10^4)^{0.5}}{0.6/0.707 + 0.95/0.707^{1/3}} = 47.17$$

Using Eq. (3)

$$h = \frac{Nu_r \lambda}{r} = \frac{47.17 \times 2.44 \times 10^{-2}}{100.4 \times 10^{-3}} = 11.46\ \mathrm{W/(m^2 \cdot K)}$$

$$\Phi = \int_{r_1}^{r_2} h(t_d - t_\infty)(2\pi r)\,\mathrm{d}r = h(t_d - t_\infty)\pi(r_2^2 - r_1^2) = 11.46 \times (283 - 273)\pi(100.4^2 - 49.6^2) \times 10^{-6} = 2.74\ \mathrm{W}$$

2.3 Heat transfer through heat-insulating layer and determination of its thickness

In reference to Eq. (6)

$$q_2 = \frac{t_1 - t_4}{\dfrac{\delta_1}{\lambda_1} + \dfrac{\delta_2}{\lambda_2} + \dfrac{\delta_3}{\lambda_3}} = \frac{283 - 263}{\dfrac{0.02}{2.2} + \dfrac{\delta_2}{0.025} + \dfrac{0.02}{28.5}}$$

Assuming that $\delta_2 = 0$, i. e., the heat-insulating layer is not placed, $q_2 = 2\,042.34\ \mathrm{W/m^2}$. Then the heat transfer through the bottom is, $\Phi_2 = S_2 q_2 = 64.68$ W. And the heat generated due to friction can be expressed as $\Phi_1 = S_1 r q_1 = 0.74$ W.

In this situation, the heat causing the melt of the ice pad is mostly coming from the bottom, accounting for about 94.89%. Consequently, heat-insulating layer is needed to increase the service life of the ice pad. When $\delta_2 = 0.02$ m, $q_2 = 24.70\ \mathrm{W/m^2}$. The heat transfer through the bottom is, $\Phi_2 = S_2 q_2 = 0.78$ W. In this case, the heat causing the melt of the ice pad mostly comes from the top surface, accounting for about 64.32%.

Assuming that heat transfer through the bottom of the total is less than 20%, and substituting $S_2 q_2 < \frac{1}{4}(S_1 q_1 + \Phi)$ from Eq. (6), one thus has

$$\delta_2 > \lambda_2\left[\frac{4S_2(t_1 - t_4)}{S_1 q_1 + \Phi} - \frac{\delta_1}{\lambda_1} - \frac{\delta_3}{\lambda_3}\right] \tag{7}$$

It can be derived that the thickness of the heat-insulating layer should be more than 17.96 mm accordingly. Considered the "Shoveling ice" phenomenon, the thickness of heat-insulating layer is set as 20 mm eventually.

Polytetrafluoroethylene (PTFE) was chosen as the heat-insulating layer material first, which is characterized as the material with low-temperature resistant, good mechanical toughness, corrosion resistance and good wear resistance. In addition, this material has a low thermal conductivity which can prevent excessive melt of the ice. But one phenomenon was discovered later, that is, PTFE heat-insulating layer would be warped due to its "cold flow". Plastic deformations will be caused in PTFE product due to its creep behavior under continuous load. So polyurethane was finally chosen as the material of the heat-insulating layer instead of PTFE.

The ice fixed abrasive pad with the original cast iron base is shown in Fig. 2. The mold of ice fixed abrasive pad with Polyurethane heat-insulating layer is shown in Fig. 3. Red part in Fig. 3 is Polyurethane heat-insulating layer placed on the original cast iron base. There are some annular grooves and a cross groove on the surface for fixing the ice pad. The average thickness of the heat-insulating layer is about 20 mm.

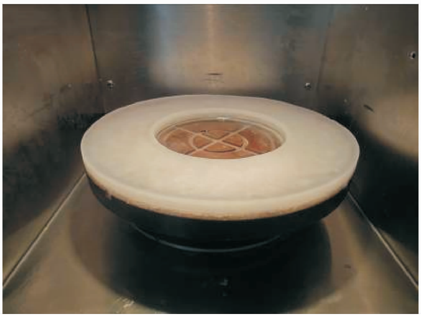


Fig. 2 Ice fixed abrasive pad with the original cast iron base

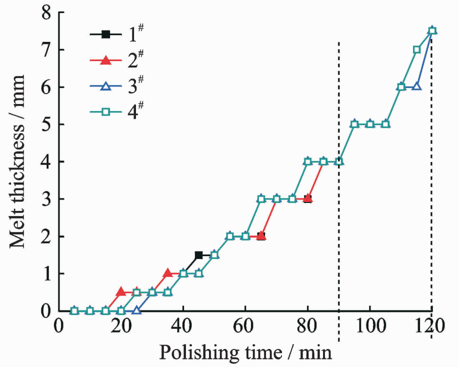
Fig. 3 Mold with Polyurethane heat-insulating layer

3 Experiments

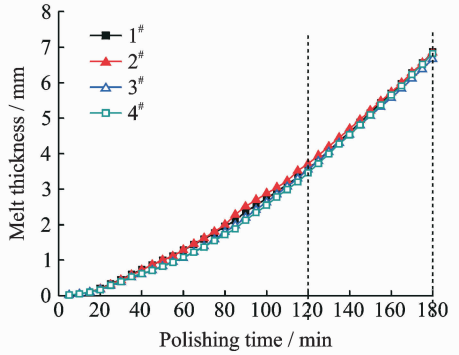
The experiments with the mold added heat-insulating layer are repeated as the experiments with layered ice fixed abrasive polishing pad[15]. Four steps are included in the polishing process, as shown in Table 1. Namely, 1#: micron α-Al_2O_3 abrasive, polishing eccentricity $e = 105$ mm, polishing pressure $p = 0.025$ MPa, spindle speed $\omega = 100$ r • min^{-1}, the polishing time $t = 90$ min. 2#: micron α-Al_2O_3 abrasive, polishing eccentricity $e = 75$ mm, polishing pressure $p = 0.025$ MPa, spindle speed $\omega = 100$ r • min^{-1}, the polishing time $t = 90$ min. 3#: nano-SiO_2 abrasive, polishing eccentricity $e = 90$ mm, polishing pressure $p = 0.075$ MPa, spindle speed $\omega = 200$ r • min^{-1}, the polishing time $t = 30$ min. 4#: nano α-Al_2O_3 abrasive, polishing eccentricity $e = 75$ mm, polishing pressure $p = 0.05$ MPa, spindle speed $\omega = 200$ r • min^{-1}, the polishing time $t = 30$ min. Thickness melting curves of four kinds of the polishing pads during polishing are shown in Figs. 4(a, b).

Table 1 Process parameters of different layered ice fixed abrasive polishing

Polishing parameter		Layered pad type	
		Micron α-Al_2O_3-nano SiO_2 layered polishing pad	Micron-nano α-Al_2O_3 layered polishing pad
Eccentricity/mm		105	75
Micron layer	Pressure/MPa	0.025	0.025
	Velocity/(r • min^{-1})	100	100
	Time/min	90	90
Nano layer	Pressure/MPa	0.075	0.05
	Velocity/(r • min^{-1})	200	200
	Time/min	30	30



(a) Melt thickness without heat-insulating layer[15]



(b) Melt thickness with heat-insulating layer

Fig. 4 Melt thickness with and without none heat-insulating layer

After placing the heat-insulating layer, the main heat flow into the ice pad is the heat transfer from the top surface instead of the bottom. It helps the ice pad melt for self-sharpening in order to exposing new abrasives, thus improving the polishing quality. The decrease in overall heat flow and simplification of the process of heat transfer, make the melting rate of the ice pad more gentle.

Fig. 4 shows that the service life of ice fixed abrasive polishing pad is increased from 120 min to 180 min by the heat-insulating layer. And the melting process of ice fixed abrasive is more stable. It is helpful to improve the quality of polishing. Following the conservation of heat, to melt an ice fixed abrasive pad with thickness of 7 mm, 51 100 J heat will be needed. The heat dissipation rate with the existence of the heat-insulating layer is 4.76 W, with which the total time of 178.9 min will be needed for the ice pad to melt. It agrees well with the melting rate obtained from the repeated experiments, as shown in Fig. 4(b).

4 Conclusions

The service life of ice fixed abrasive polishing pad is increased effectively by the Polyurethane heat-insulating layer. And the melting rate is also reduced during the polishing process to improve the polishing efficiency. According to the theoretical formulas, the thickness of the heat-insulating layer is derived. The correctness of the equation is validated by the repeated experiments. A theoretical basis and a calculation method for the temperature field of ice fixed abrasive polishing are provided via the analysis of heat transfer model for future studies.

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