Modeling of lapping plate wear and conditioning in single-sided lapping

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1 Introduction

Lapping is a critical technology in a number of precision manufacturing applications and it is defined as a low-velocity and low-pressure finishing operation in which small amounts of material are removed from the workpiece by means of loose abrasive grains. The process can be classified as single-sided lapping or double-sided lapping. When only one side of the work material is lapped against the lapping plate, the process is regarded as a single-sided lapping. This process is one of the most effective and commonly used planarization technologies. However, to achieve higher quality on worked surfaces with lower roughness, very high accuracy of shape and dimensions it is crucial to improve conventional finishing technologies and to develop new working principles [1].

The system of single-sided process includes several elements: lapping plate, abrasives, lapped workpieces, kinematics and machine. They are factors that influence the lapping process, which determines the product quality, tool wear and efficiency of the process [1, 2]. Moreover, the input factors of lapping process can be categorized as: controllable and non-controllable factors. Machining parameters, it is working pressures and speeds, abrasive type, characteristics of the work equipment, tool, machine, duration of machining belong to the first group. The uncontrolled input variables, which are called noise factors includes environmental temperature, slurry distribution, vibrations occurring in the system, internal stress etc. An overview of influencing factors and outcomes in lapping process is presented in Figure 1.

The most critical parameter, which influence the surface formation and material removal rate in lapping process is the lapping plate, its geometry, properties and initial condition. Generally, it can be assumed that workpieces are machined to a mirror image of the lapping plate with respect to the flatness. Since, the wear of the lapping plate is not constant over the diameter, it does not remain flat and the following shape errors can occur: convexity, concavity and axial runout [3, 4]. Therefore, research should focus on improving lapping process by studying process conditions, flatness control and tool conditioning.

In this paper a comprehensive study of the material removal mechanisms in abrasives process was presented. The model of lapping plate wear in single-sided lapping was created and in detail analyzed. Matlab program was designed to simulate the abrasive particles trajectories and to count their distribution. It was observed, that a trajectories distribution of abrasive particles on the lapping plate varies when the running parameters and kinematics of conditioning ring movements are changed. Recommended kinematic parameter settings of single-sided lapping process were presented.

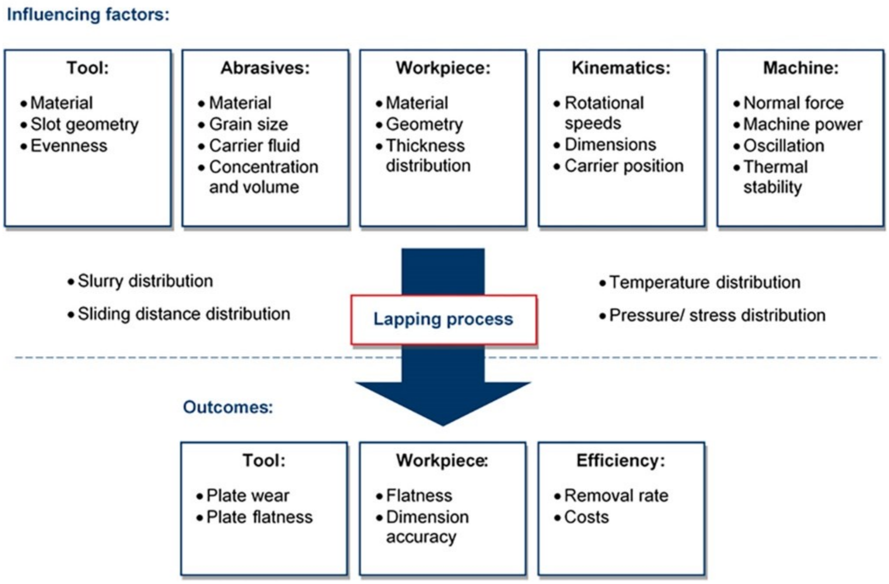

Figure 1: Influencing factors in lapping process

2 Single abrasive trajectories simulation

Lapping, grinding, polishing, and CMP (chemical-mechanical polishing) are all techniques used for precise removal of material. The machines for finishing operations vary extensively depending upon the application and manufacturer. However, most of the machine tools manufactures offer planarization technology on lapping machines or machines with lapping kinematics. The single-sided lapping machines have the standard kinematic system (Fig. 2a) equipped with single annular-shaped plate (1) and usually have three to four conditioning rings (4). The lapping plate rotates with angular velocity ω_t and drives conditioning rings, where separators (3) are placed, allowing additional move of workpieces (3). Conditioning rings rotate with angular velocity ω_s, by the frictional force. This force depends on a radial position, velocity of conditioning rings, friction conditions and load, which is provided through felt pad by weight disk or pneumatic system. The radial position of conditioning rings R_p can be controlled with roller forks [4].

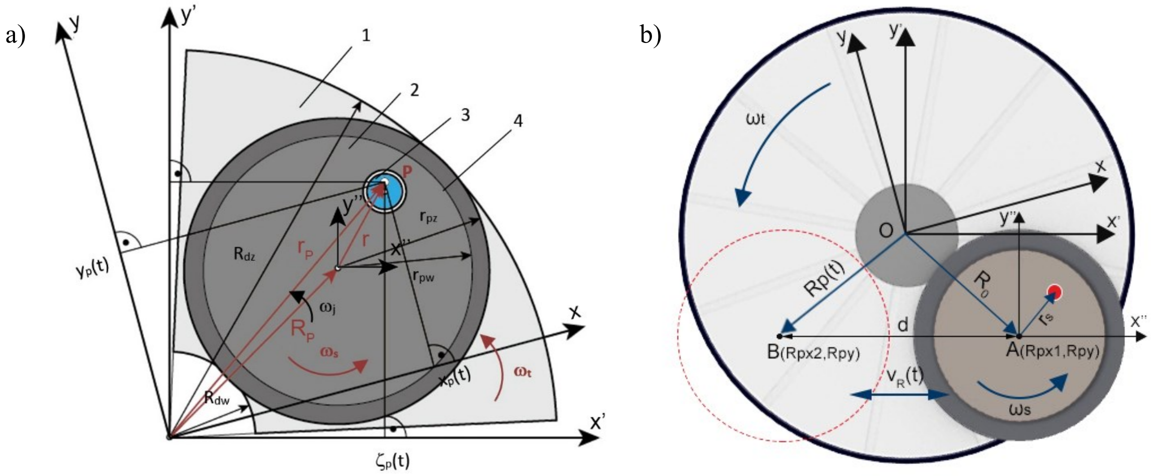

Figure 2: Kinematic diagram of single-sided lapping machine: a) conventional, b) with reciprocating motion of conditioning ring

In order to model a lapping plate the position of any point P belonging to a workpiece or conditioning ring must be determined. This point can be treated as a grain placed in a specific location. The position can be determined by a radius vector in two coordinate systems: absolute and relative, which is related with rotating tool. However, conducted simulations have shown that changing the kinematic system in single-sided lapping process causes a wide density variation of single abrasive trajectories, which could have positive influence on lapping plate wear. The detailed kinematic diagram of single-sided lapping system with the additional movement of conditioning ring is presented in Fig. 2b. In this idea, there is only one conditioning ring, which in addition to rotary motion performs a reciprocating motion along a chord and between points A and B. The position of the conditioning ring is not constant as in conventional system, parameter $R_{Px}(t)$ changes the value in time. The distance from the center of the lapping plate to the chord equals R_{Py}.

The position of any point $P(r,\varphi p)$ belonging to a workpiece in single-sided lapping system is determined in x''y'' coordinate system, which is related to conditioning ring as:

$$x_P'' = -r \cdot \cos(\varphi_s) \tag{1}$$

$$y_P'' = -r \cdot \sin(\varphi_s) \tag{2}$$

The coordinates of point P in x'y' coordinate system are:

$$x_P' = x_P'' \cdot \cos(\omega_s \cdot t) + y_P'' \cdot \sin(\omega_s \cdot t) + R_{Px}(t) \tag{3}$$

$$y_P' = -x_P'' \cdot \sin(\omega_s \cdot t) + y_P'' \cdot \cos(\omega_s \cdot t) + R_{Py} \tag{4}$$

The coordinates in system related to rotating lapping plate are:

$$x_P = x_P' \cdot \cos(\omega_t \cdot t) + y_P' \cdot \sin(\omega_t \cdot t) \tag{5}$$

$$y_P = -x_P' \cdot \sin(\omega_t \cdot t) + y_P' \cdot \cos(\omega_t \cdot t) \tag{6}$$

The following equations were implemented in MATLAB program. The program allows to analyze single-side lapping system and can be used to mark out cycloids paths of any point, which can be treated as areas where the lapping plate wears by the grain placed in a specific location of a conditioning ring or workpiece. Figure 3 shows an example of single abrasive trajectories on lapping plate at different times. The trajectories are marked out with blue color. Moreover, in Fig. 3a trajectory of the conditioning ring is marked out with green color and real trajectory of the single abrasive with red color.

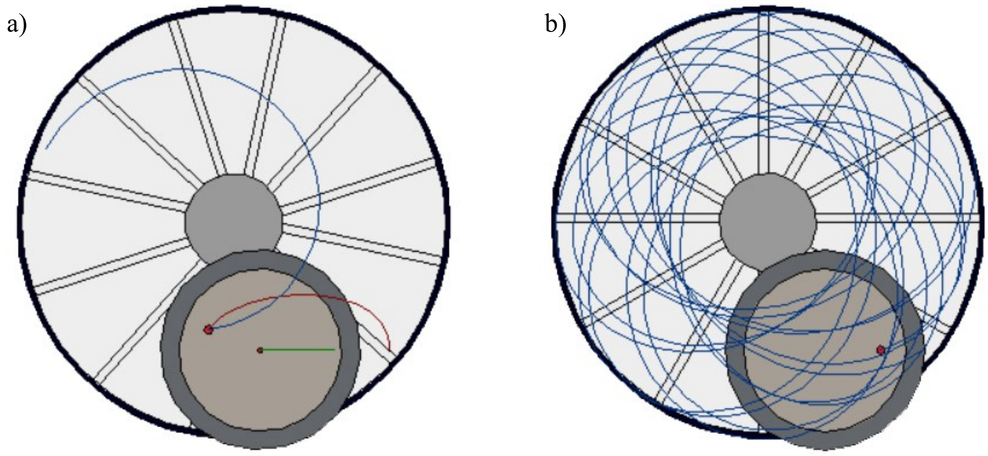

Figure 3: Example of single abrasive trajectories at different times: a) t=2 s, b) t=120 s

3 Lapping plate wear model

There are many researches that describe model of material removal rate (MRR) during finishing operations. Several researchers worked on experiment and analytical models [5, 6]. Also in case of lapping process, the volume of material removed by lapping process at a local position during every unit of time is an important part of study. The considerations about MRR are crucial, because it is the only solution to provide the maintenance of reliability and lifetime of the produced workpieces. The most popular method to predict the profile wear of the abrasive processes is the tribological model developed by Preston. The model that was developed based on the effects of grinding glass, relates relative velocity v, constant k and pressure p to material removal rate. The parameter k varies based on any modifications to the material removal process such as abrasive and slurry type, feed rate, and other process parameters [5]. However, in single-sided lapping Preston's coefficient k and force per unit area p are constant in time. The value change only the relative velocity of lapping v, which can be calculated from the kinematic equations.

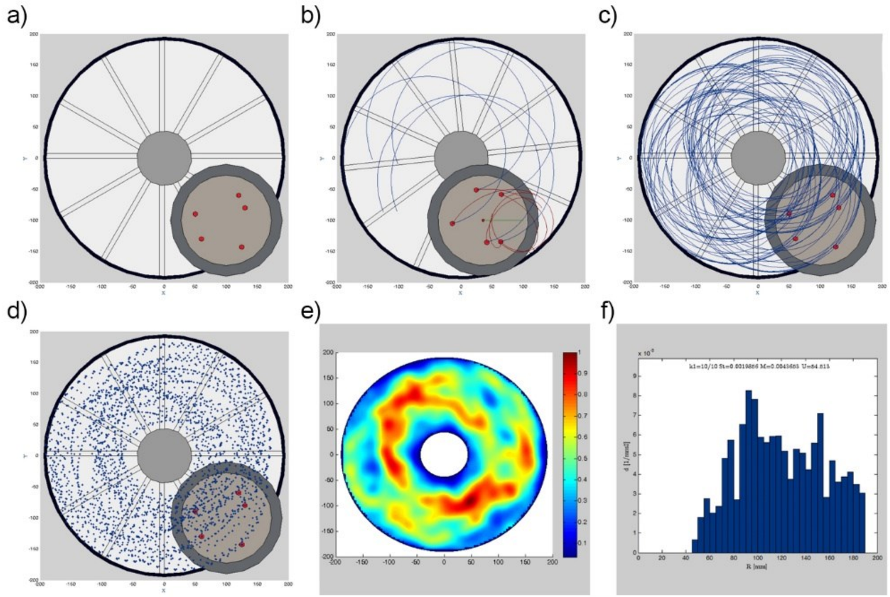

Figure 4: Trajectories density determination: a) random generated particles b-c) trajectories generating, d) trajectories interpolation, e) density of trajectories, f) profile density of trajectories

Another fairly common model of the lapping plate wear assumes that the wear intensity depends on a contact intensity of the tool with the workpieces through the lapping abrasive grains [7, 8]. A Matlab program was designed to simulate the trajectories and to count their distribution. In order to determine the contact intensity, the program calculates a particles density of interpolated trajectories. The example of the calculation steps for the case of 5 random particles is shown in Fig. 4. In first step, the particles locations are determined within the conditioning ring using a random function (Fig. 4a). The trajectories of the particles are generated with a use of the kinematic equations (Fig. 4b-c). In order to calculate a set of points, which are equally spaced from each other (4d) an interpolation function is used. Then the lapping plate surface is divided into equal areas. To count the total number of points within each area of the lapping plate surface, a statistics function is used (Fig. 4e). Finally, to determine if the wear causes a concavity or the convexity, the contact intensity can be developed for a profile of the tool (Fig. 4f). It can be achieved by dividing the area of the lapping plate into equal rings.

The density is a measure of the points in in an appropriate area and it is determined by equation:

$$D_i = \frac{n_i}{A_i - A_{i-1}} = \frac{n_i}{(2i-1)\cdot\pi\cdot r^2} \tag{7}$$

where: n is a points number in area A_i and r is rings width.

4 Parameters optimization

It was observed, that the parameters affecting trajectory distribution are the rotational speed ratio k_1 of the conditioning ring to the lapping plate and the period ratio k_2 of the reciprocating motion of the conditioning ring to rotary motion of the lapping plate, which represent the relationships among the three basic motions of unconventional lapping systems. The optimization of both parameters is important to obtain a better uniformity base on trajectory simulations and consequently even lapping plate wear. The trajectories distribution uniformity is defined:

$$U = (1 - \frac{S_D}{\overline{D}})\cdot 100\% \tag{8}$$

where S_D is the standard deviation of trajectories density, and $\overline{D}$ is the average value of the trajectories distribution.

There are more than one million active particles in the slurry and on the lapping plate during the lapping process. An appropriate particle number, which does not prolong time of the calculation and can reflect the same regularity as the real number, has to be determined. Figure 5 shows the influence of the particles to the uniformity. Results are presented for standard single-sided lapping system, when k_1=0,45 and radial position of conditioning ring R_P equals 125 mm. It was observed, that for more than 1000 particles uniformity is stable and constant.

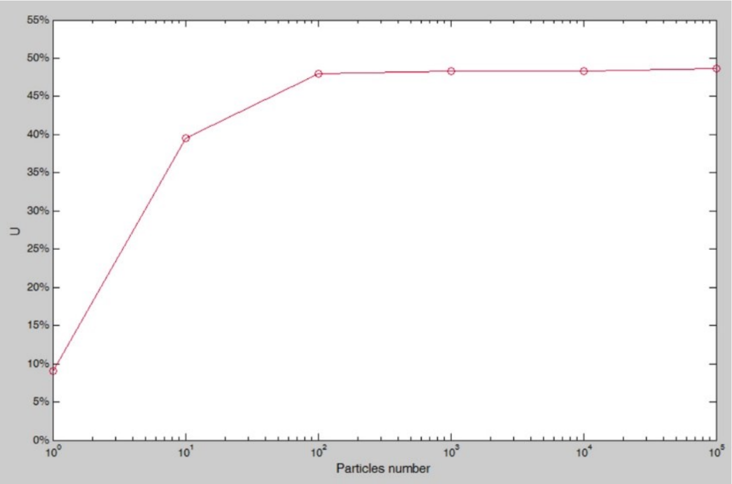

Figure 5: Uniformity of trajectories distribution produced by different number of random particles

The uniformity of trajectories density for standard single-sided lapping system and for single-sided lapping system with reciprocating motion of conditioning ring is presented in Figure 6. Trajectories were generated for 100 random particles during 60 seconds on lapping plat with internal diameter of 88 mm and outer diameter of 350 mm. It was observed that in conventional lapping system the maximum uniformity was obtained when k_1=0.8~1.0. The results show also the beneficial effect of additional ring movement. In non-standard lapping system the uniformity increased by more than 12%, when k_2=1.

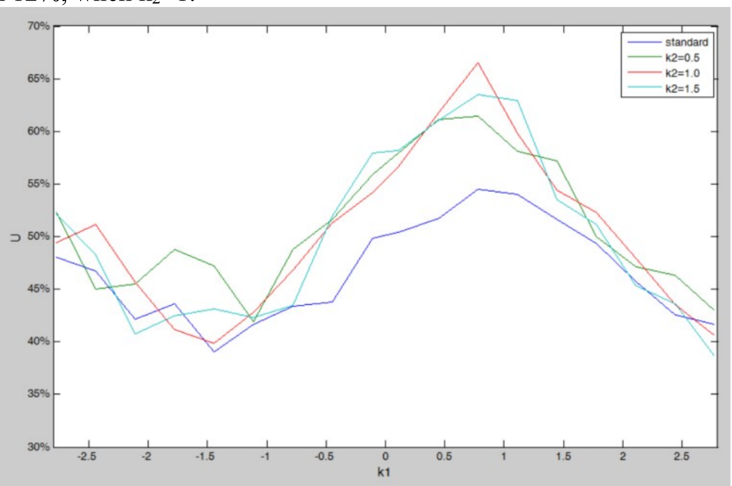

Figure 6: Trajectory density uniformity versus k1 for standard and non-standard single-sided lapping system

5 Conclusions

In the paper, the influence of selected factors on the geometrical results of the single-sided lapping process was presented. Furthermore, the unconventional single-sided lapping system, where a conditioning ring performs an additional movement during the machining, was described and particles sliding trajectories were numerical simulated. It was observed that changing the kinematic parameters, e.g. rotational velocities or position of the conditioning rings together with the workpieces can be used for correcting the profile of an active surface of the lap. The main parameters that affecting trajectory distribution are the rotational speed ratio k_1 of the conditioning ring to the lapping plate and the period ratio k_2 of the reciprocating motion of the conditioning ring to rotary motion of the lapping plate.

In order to improve the quality and flatness of the machined surfaces, the optimization of these parameters was conducted. Main optimization criterion was the uniformity of tool wear. In conventional single-sded lapping system, the maximum uniformity was obtained when $k_1=0.8\sim1.0$. The results showed also the beneficial effect of single-sided lapping system with reciprocating motion of conditioning ring, where the uniformity increased by more than 12%, when $k_2=1$.

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