Experimental Study on Surface Roughness and Flatness in Lapping of AISI 52100 Steel

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Abstract: Lapping is one of the most important polishing processes which can be used to fabricate flat and smooth surfaces. In this paper, the effect of lapping characteristics and mesh number of abrasive particles are studied on the surface roughness and flatness for the machining of hardened AISI 52100 rings. The most significant lapping characteristics are pressure, lap plate speed and time. Scanning electron microscopy and optical microscopy are used to investigate micro cracks and surface textures. Results showed that surface roughness increases by rising the lapping pressure and plate speed. Also, reduction of the lapping time and mesh number of abrasive particles led to lower surface roughness. Application of lapping process decreased the flatness to 1.2 μm and surface roughness (Ra) from 0.58 to 0.051 μm. The lapping pressure was a significant factor on the surface roughness; and the lapping time was a significant factor on flatness. However, surface roughness was increased by rising of mesh number and lapping time, and was increased by decreasing the lapping pressure. The minimum surface roughness was 0.051 μm which was obtained in lapping pressure of 7 kPa, lapping speed of 0.164 m/s, time of 15 min and mesh number of 600.The flatness decreased with lapping speed, and was reduced with increasing the pressure, mesh number and lapping time.

Keywords: ANOVA, Flatness, Hardened Steel, Lapping, Surface Roughness

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1 INTRODUCTION

Lapping is a fine finishing process in which abrasive particle play an important role to perform the cutting process. In this process, the abrasive slurry is injected to the top surface of lap plate, then the lap plate polishes the flat or round workpiece. Due to the relative rotational motion between the lap plate and workpiece, the workpiece face is polished and flattened. The lapping of flat surfaces is the most common lapping processes [1], [2]. Abrasive wear is defined as material removal with slow rate which happens due to the relative motion of abrasive particles. Abrasive wear can be classified to two categories as follow: a) two-body abrasion and b) three-body abrasion. In three-body abrasion, the abrasives grains have free motion between workpiece and the tool surface which results in wear on the surface of work piece; but in two-body abrasion, the abrasive particles is attached to the tool surface and can lead to wear of the workpiece.

In two-body mechanism and due to attachment of particles to the tool surface, each particle can perform cutting with large deep. In three-body abrasive machining such as lapping process, abrasive grits tumble on the workpiece surface while a downward force is applied. The force is distributed on grits, so each abrasive particle rolls between the workpiece and lap plate. During rolling motion, the sharp edge of grits penetrate to the workpiece surface. Combination of penetration and motion leads to removal of workpiece material [3].

The heat generation in lapping process of glass workpiece was investigated by Bulsara et al., [4]. They suggested each abrasive particle as a mobile thermal source applied to the contact of abrasive grains and workpiece. Then, they calculated the maximum and average of the temperature rise during lapping process. Their calculations estimated the temperature below 200˚C. Chang and Dornfeld [5] found two important parameters to explain the mechanism of material removal during lapping process. Mentioned parameters were ductile against brittle machining and two body against three body abrasion. Uhlmann and Ardelt [6] studied the kinematic of relative motions in lapping machines. Their results indicated that changing the path type of relative motion improves the flatness and surface roughness.

Various parameters are effective on the surface roughness and flatness of the workpiece such as lapping speed, time, pressure and the mesh number of abrasive particles. The normal pressure and crystal direction of material have significant effect on the material removal rate and surface roughness [7]. Mamalis et al. discussed the mechanism of material removal in lapping process of alumina, in the presence of synthetic diamonds with different sizes. They concluded that achieving the remarkable smoothness of lapping process in finishing mode initially occurs due to plastic deformation and smearing of alumina particles on related surfaces [8].

Chang et al., [9] conducted the lapping process on the gauge block. Their results showed that using Al_2O_3 particles improves surface quality more than application of SiC particles. They found that the surface roughness was improved by decreasing the mesh number of abrasive particles. The optimum conditions were obtained in pressure of 18.75 kPa and lapping speed of 150 RPM. Tam et al., [10] studied lapping process which was applied to RB-SiC optical workpiece. They suggested two stages: in the first step, they used fixed diamond pellets on the table for high speed lapping. In the second stage, they used abrasive grains by average diameter of 10 μm to 1 μm to achieve a smooth surface.

Belkhir et al., [11] investigated the relationship between the abrasive grains and surface quality in lapping of glass. They observed some phenomena in wear of abrasive grains: the wear phenomena rounded the edges of grains and the fracture of grains led to changing the edges angles. Deshpande et al., [12] studied the influence of abrasive grain hardness on the surface quality in the case of stainless steel and bronze workpieces. They used three kinds of abrasive grains: Garnet (hardness of 8 Mohr), Alumina (hardness of 9 Mohr) and Crystolon (hardness of 9.5 Mohr). They found that surface roughness and flatness improves by increasing the grains size, but produces fine cracks on the surface. To reduce the cracks on the surface, they suggested that the lapping process starts with coarse and hard grains, then continues with fine and pretty hard grains.

Mohan and Babu prepared the polishing tool with ice-bonded abrasive to finish flat surfaces of copper and stainless steel workpieces [13-15]. They concluded that lower rotational speed tool with low abrasive particles concentration and raising of pressure could improve the finishing of workpieces up to 55% and produce scratch free surfaces. Tsai et al. made hydrophilic chemical-mechanical composite polishing pad, so the polyurethane matrix was impregnated by graphite particles in submicron size. Increasing the graphite up to 15% increased the material removal rate, and material removal rate was decreased by increasing of graphite more than 15% [16]. Tian et al. studied chemical mechanical polishing process by using fixed pad as an alternative of loose lapping [17].

Dong and Cheng studied the removal mechanism in lapping of SiC by using fixed abrasive diamond pellets [18]. As mentioned, numerous experimental researches have studied the surface roughness in lapping process, and few researchers have attempted to study the flatness of lapped workpiece. But the simultaneous study on the surface roughness and flatness of hardened steel has not yet been done. To this, there is a need to explore the effect of various parameters in lapping process. In addition, the study on the mechanism of material removal is essential to understanding of the lapping parameters to adjust them to achieve required the surface roughness and flatness. In this research, the lapping process on hardened steel rings is analysed. In this study the effect of lapping characteristics such as abrasive grain size, lapping speed, time and pressure on flatness and surface roughness of AISI 52100 steel workpiece is investigated. To determine the influence of lapping parameters on the flatness and surface roughness, the design of experiments and analysis of variance are employed.

Fig. 1 The Lapping process

(a) (b)

Fig. 2 a) The workpiece,
b) Surface roughness measurement

2 MATERIALS AND METHODS

The lapping machine, used in this study, was made in Nahadin Sanat Sofe Co. (Iran) with the power of 0.5 kW, the rotational speed of 0 to 60 RPM. Lapping machine included a cast iron lapping plate with the diameter of 350 mm and the lapping rings with the diameter of 125 mm (Fig. 1). The workpiece was AISI 52100 steel with hardness of 45 HRC. The workpiece had a ring shape with the thickness, inner and outer diameter of 10, 52 and 63 mm, respectively (Fig. 2.a). The initial roughness of workpiece was 0.58 $\pm$ 0.04 μm.

The surface roughness of workpieces before and after lapping, represented by the parameter Ra, was measured by PERTHOMETER M2 (Mahr, Germany) instrument (Fig. 2.b). The cut-off and traversing length values were 0.8mm and 5.5mm, respectively. For each test, 3 measurements were conducted over the face of workpiece and subsequently, the mean value of results were recorded. The Flatness was measured by optical flat by the red ray with wave length of 0.622 μm. In this way, the optical flat is putted on the face of workpiece and the red ray was radiated on the optical flat. Scanning electron microscopy (SEM) was employed to investigate the influence of the lapping on the surface texture.

2.1. Experimental procedure

At first, the abrasive slurry was injected on the cast iron plate of lapping machine with a constant rate, continually. The workpieces were placed inside the rings of the machine and then the related weights were mounted on the workpieces to apply vertical load. This vertical load produced lapping pressure. The lapping pressure can be changed by changing the mass of the weights. The rotation of the lap plate made centrifugal force and caused the workpiece to move in radial direction. The relative movement between the face of workpiece and lap plate caused an effective layer of abrasive grits between them. This slurry under the pressure removed workpiece asperities, gradually.

To investigate the effect of lapping parameters (pressure lapping, lapping speed, lapping time and mesh number) on the surface roughness and flatness, the experiments with specific levels (Table 1) were conducted.

Table 1 The levels of lapping parameters

Symbol	Parameters	Level1	Level2	Level3
P	Pressure (kPa)	7	11.5	15.5
V	Lapping speed (m/s)	0.164	0.33	0.495
MS	Mesh number	200	400	600
T	Time (min)	5	10	15

3 RESULTS AND DISCUSSION

The effects of lapping parameters on surface roughness and flatness are investigated in the following sections.

3.1. ANOVA

ANOVA is an appropriate statistical method to recognize which parameters effect on the response of the inquired process through the series of experimental results. The analysis of variance was employed to investigate the influence of lapping parameters on the surface roughness (Table 2) and flatness (Table 3). These analyses were carried out for a level of significance of 5%, i.e., a level of confidence of 95%. The last columns in Tables 2 and 3 indicate the percentage of contribution of each factor to the total variation, indicating the degree of influence on the results. From Table 2 and Table3, it can be revealed that lapping pressure (with contribution of 64.30%) is a significant factor which effects on the surface roughness. Also, the lapping time (with contribution of 42.8%) has significant effect on the flatness.

Table 2 ANOVA on the results of surface roughness

Parameter	DF	Seq SS	Ms	F	P	C (%)
P (kPa)	2	0.01245	0.00079	33.3	0.0	64.3
V (m/s)	2	0.00116	0.00058	24.4	0.0	5.8
MS	2	0.00269	0.00134	56.6	0.0	13.7
T (min)	2	0.00256	0.00128	54.0	0.0	13.0
Error	18	0.00042	0.00002			
Total	26	0.01930				

Table 3 ANOVA on the results of flatness

Parameter	DF	Seq SS	Ms	F	P	C (%)
P (kPa)	2	0.79705	0.7931	28.88	0.000	23.8
V (m/s)	2	0.54003	0.2700	8.81	0.002	15.5
MS	2	0.41106	0.2055	6.71	0.007	11.3
T (min)	2	1.38275	0.6913	22.56	0.000	42.8
Error	18	0.55167	0.0306			
Total	26	3.68256				

3.2. The influence of lapping pressure and time

The results of the influence of lapping pressure at different times (5, 10 and 15 min) are shown in Fig. 3. All experiments are carried out in lapping speed of 0.164 m/s and by the size of 200. As can be seen in Fig. 3, by increasing the pressure at any time, the surface roughness increases. The surface roughness increased about 27 % in the pressure of 15.5 kPa during machining time of 15 min in comparison to lapping pressure at time of 7 kPa and 5 min, respectively. By increasing lapping pressure, the normal force on a single abrasive on surface increases.

So, the penetration depth of abrasive particle increases which finally results in more material removal and surface roughness. In Figure 3, it can be found that the surface roughness decreases by increasing time from 5 min to 15 min in constant pressure and speed. For example, surface roughness under pressure of 7 kPa and cutting speed of 0.164 m/s, decreases about 25% for lapping time of 15 min in comparison to 5 min. Also, increasing lapping time leads to more material removal and results to remove the roughness of previous process. This trend improves the surface roughness.

Figure 4 shows optical microscopy photograph of samples before lapping (Fig. 4.a), after lapping pressure of 15.5 kPa (Fig. 4.b), and after lapping pressure of 7 kPa (Fig. 4.c). As can be seen in Fig. 4, the number of scratches in 4-b is fewer than 4-a, which presents the effect of lapping process on reduction of surface scratches. By comparing Fig. 4.b and Fig. 4.c, it can be seen that, in lower pressure, the depth of scratches is lower and the surface roughness is improved.

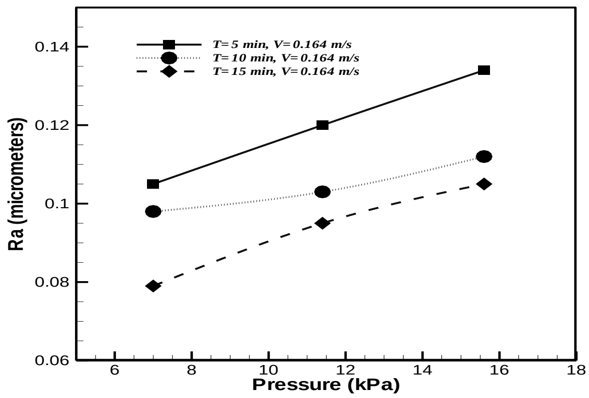
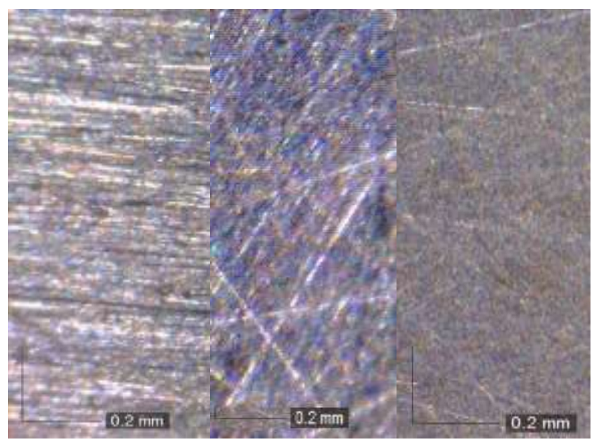


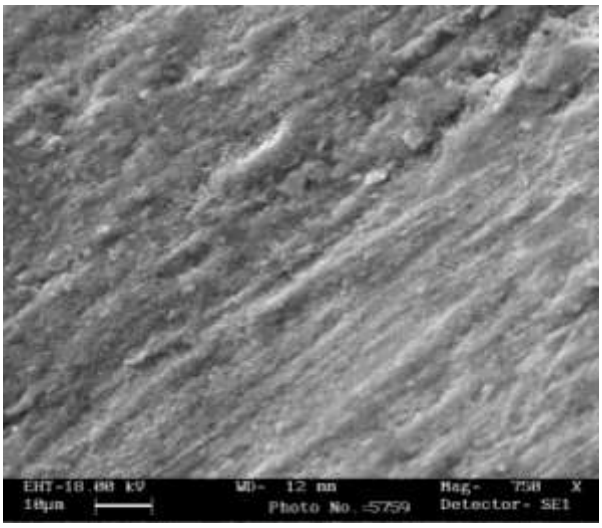
Fig. 3 The influence of lapping pressure and time on the surface roughness



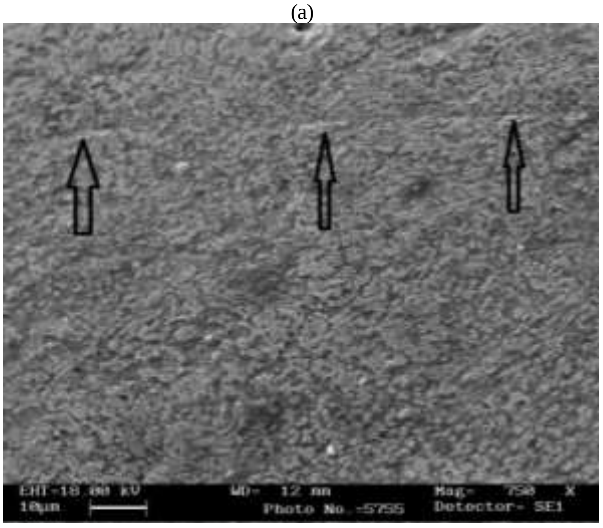
(a) (b) (c)

Fig. 4 Optical microscopy photograph, a) before lapping, b) lapping in p=15.5 kPa, t=5min, c) lapping in p=7 kPa, t=5min

To investigate texture of lapped face, two samples were selected to study by the SEM. The first sample is before lapping process (Fig. 5.a), and second sample is after lapping process with pressure of 7 kPa and the time of 15 min (Fig. 5.b). In the Fig. 5.b, the surface is smooth and surface roughness is lower than the sample in Fig. 5.a. In the Fig. 5.a, the scratches can be seen, which are shown by arrows. These scratches present the wear of face by abrasive particles in cutting process. In fact, the abrasive particles create scratches on the face of workpiece in cutting process [12]. So by increasing the pressure, scratches increase and surface roughness increases, too.



(a)



(b)

Fig. 5 SEM photograph of a) the sample before lapping, b) the sample after lapping with p=7 kPa and t=15 min.

Parallel scratches in Fig. 6.a represents two-body mechanism of grinding. In Fig 6.b these parallel scratches were removed and splotch texture appears which represents the three-body mechanism in the lapping process. This Fig shows how lapping process removes the roughness of surface and leads to improvement in the surface roughness. As shown in Fig. 6.b, in pressure of 7 kPa, the material removal mechanism is three-body wear. However there are few scratches that represent the two-body wear. The reason of two body scratches may be for unequal grain size of abrasive particles. Fig. 6 shows the influence of lapping pressure on flatness at various times. The experiments have been done in constant lapping speed of 0.164 m/s and the mesh number of 200. As shown in Fig. 6, the flatness decreases with increasing of lapping pressure and time. The increasing pressure and time reduces the height of peaks on the surface. Also more pressure causes workpiece surface tend to be shaped more flat. Based on the obtained data from experiments, the maximum flatness is 2.7 µm in pressure of 7 kPa, and time of 5 min, and the minimum flatness is 1.5 µm in pressure of 15.5 kPa and time of 15 min.

The experiments have been done in constant pressure of 7 kPa and constant lapping speed of 0.164 m/s. The mesh number of abrasive particles is 200, 400 and 600 (in highest mesh number the abrasive is finest). It can be found from Fig. 7.a that surface roughness decreases with increasing of mesh number. The surface roughness in lapping time of 5 min reduced from 0.087µm for mesh number of 200 to 0.052 µm for mesh number of 600, which shows a reduction of 67%. The mesh number of abrasive particles which are used in lapping process depends on the type of machining operation (roughing or finishing). When the surface is rough, coarser particles should be used (low mesh number), because high peaks should be removed by coarse particles. Also, small peaks should be removed by fine particles. The penetration of a single fine particle into the surface is low, and therefore the surface scratches are low. Hence reduction in mesh number increases surface roughness [9].

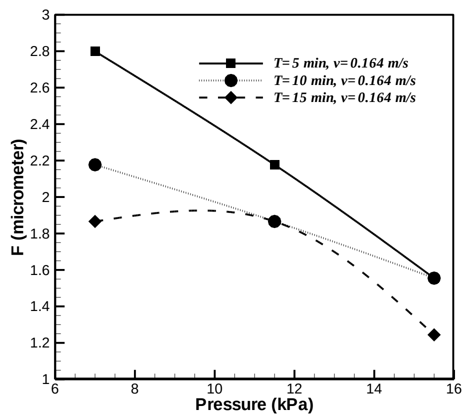
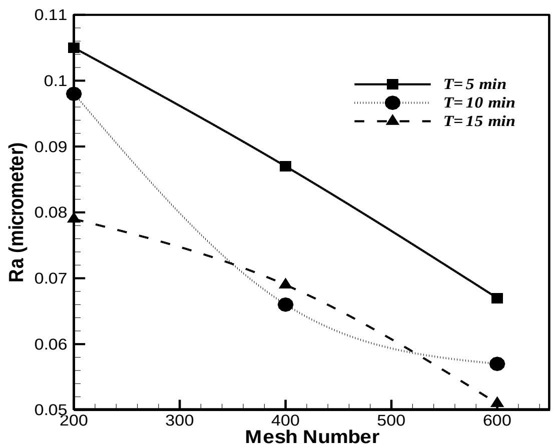


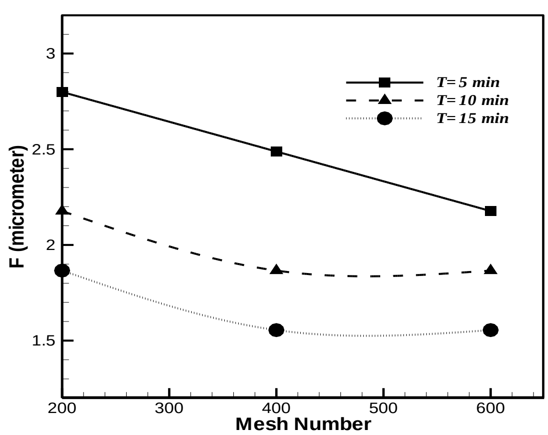
Fig. 6 The influence of lapping pressure on flatness

3.3. The influence of mesh number

The Fig. 7.a shows the relation between the mesh number of abrasive particles and surface roughness in various times. The influence of mesh number on flatness has been shown in Fig. 7.b. Flatness decreases with increasing the mesh number and lapping time. The coarse abrasive particles penetrate into the surface, and produce large cavities and rough surface. The fine particles penetrate into the surface slightly which finally leads to reduction of roughness and flatness. After beginning of lapping process, coarse abrasive particles remove the much material and it leads to previous asperities elimination. Although, after elementary shaping the surface and decreasing the flatness, coarser particles prevent the workpiece surface to settle on the lap plate. So, the workpiece floats on the course abrasive particles and shaping process of the related surface is not completed. Therefore, reduction of abrasive particles results in more flatness decreasing. The large lapping time increases the material removal and decreases peaks on the surface, as a result, decreases the flatness. The maximum flatness (2.7 μm) was obtained for mesh number of 200 under 5 min of lapping process, and minimum flatness (1.5 μm) was obtained for mesh number of 400 and 600 under 15 min of lapping process.



(a)



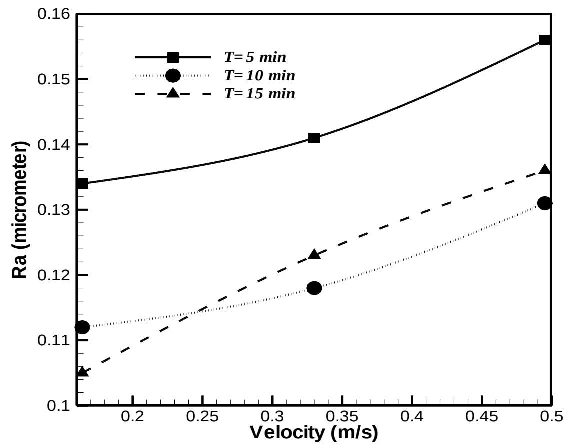
(b)

Fig. 7 The influence of mesh number on a) surface roughness, b) flatness

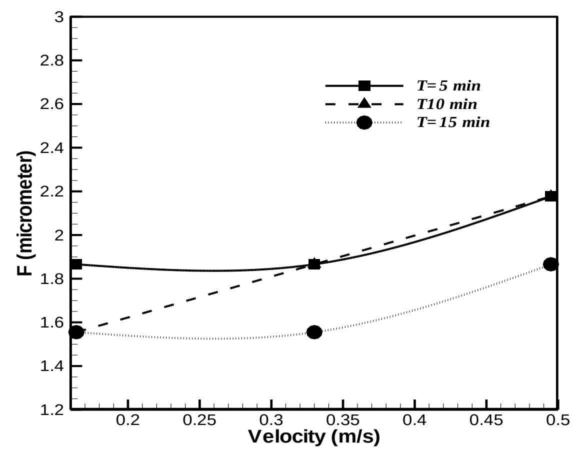
3.4. The influence of lapping speed

Fig. 8.a shows the influence of lapping speed on surface roughness in lapping time of 5, 10 and 15 min and pressure of 15.5 kPa. Based on Fig. 8.a, surface roughness increases with lapping speed. In lapping time of 5 min, surface roughness increased from 0.134 μm (lapping speed of 0.164) to 0.156 μm (lapping speed of 0.495) which shows the reduction of 16% in surface roughness. By increasing lapping speed, the kinetic energy of particles and depth of scratches increase, as a result, the material removal rate increases (which directly shows rising of surface roughness).

The influence of lapping speed on flatness has been shown in Fig. 8.b. As can be seen, the flatness increases with lapping speed. This is due to the increasing of material removal rate and increasing the vibrations of workpiece on the lap plate. The maximum flatness (2.177 μm) was obtained in speed of 0.495 m/s and times of 5 and 10 min. Also, the minimum flatness (1.5 μm) was obtained in speed of 0.164 m/s and times of 5 and 10 min.



(a)



(b)

Fig. 8 The influence of lapping speed on a) surface roughness, b) flatness

4 CONCLUSION

The main goal of this study is to investigate the influence of lapping parameters on the surface roughness and flatness of AISI 52100 steel. Based on the experimental results, the following conclusions can be drawn:

- The main material removal mechanism is three-body wear, but, due to the unequal grain size of abrasive particles, there were few scratches that are implicated on two-body wear.
- The contribution percentage of lapping pressure, mesh number, lapping time and speed for surface roughness were 64, 14, 13, and 5.8%, respectively. The contribution percentages of time, pressure, speed and mesh number for flatness were 42, 23, 15 and 11%, respectively.
- The lapping pressure was a significant factor on surface roughness, and lapping time was a significant factor on flatness. Surface roughness was increased with rising of mesh number and lapping time, and increased with decreasing of lapping pressure.
- The small peaks of roughness should be removed by fine particles. The penetration of a single fine particle into the surface is low, and therefore the surface scratches are low. The minimum surface roughness was 0.051 μm which was obtained in lapping pressure of 7 kPa, lapping speed of 0.164 m/s, time of 15 min and mesh number of 600.
- The flatness decreased with lapping speed, and reduced with increasing of pressure, mesh number and lapping time. The coarser particles prevent the workpiece surface to settle on the lap plate. Therefore, reduction of abrasive particles results in more decreasing of flatness. The large lapping time increases the material removal and decreases peaks on the surface, as a result, decreases the flatness. The minimum flatness (1.5 μm) was obtained for mesh number of 400 and 600 under 15 min of lapping process.

5 APPENDIX OR NOMENCLATURE

P = Pressure (kPa)

V= Lapping speed (m/s)

MS= Mesh number

T= Time (min)

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