Study on Lapping Process of 304 Stainless Steel Using Tribochemical Fixed-Abrasive Lapping Platen

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1 Introduction

With the rapid development of science and technology, flexible display products has become a research hotspot due to its ultra-thin, flexibility, retract ability and light weight [1-2]. Because of these excellent characteristics, it has a wide range of applications in civil field, industry field and military field [3-5].

Among these flexible display devices, select and preparation of the flexible substrate are the key of the research and development of flexible display products [6-7]. As flexible substrates, they have to have these properties, such as the ultra-thin, the high flexibility and the toughness. In addition, the flexible substrate should have high thermal stability, good chemical corrosion resistance, suitable thermal expansion coefficient and light weight [8]. All of which will directly affect the production of devices and product quality [9-10]. At present, the flexible display substrate mainly includes ultra-thin glass, polymer substrate, metal substrate and graphene [11-12].

Among these substrates, the ultra-thin stainless steel substrate has these superior properties above-mentioned, for instance the low electrostatic effect, the light weight, the curling, the strong corrosion resistance, and its coefficient of thermal expansion is close to that of glass. Because the stainless steel substrate has the good water and oxygen resistance performance, it does not need the preparation of water oxygen barrier layer. In addition, the high temperature resistance of stainless steel substrate (at least above 1000°C) is much higher than that of plastic and glass. There will be no heat resistance problem when using stainless steel substrate in the manufacturing of flexible display [13-14]. The stainless steel substrate is also suitable for the roll to roll production process, and can be directly compatible with the current semiconductor production process. So, it is easy to manufacture for TFT devices, and so on. For these reasons, the stainless steel material has these properties, such as the physical, chemical and mechanical performance and low cost, needed for the flexible display above-mentioned, and therefore which may become an ideal material for the next generation of flexible display substrate [6-8, 11-12]. Therefore, stainless steel material is very suitable for the flexible substrate material in flexible display products, which has been widely used in flexible display at present [15-16].

In a word, the stainless steel material has become the one of the flexible substrate in the manufacturing of the flexible display product in the future due to its good performance and low cost. On December 6, 2019, China
Association of special steel enterprises issued the group standard about ultra-thin stainless steel precision strip for flexible display screen, the standard No. is T/SSEA 0039-2019, which will be implemented from now on [17]. The performance of devices will be affected by the surface processing quality and accuracy [18-20]. For flexible display substrates, the surface accuracy requirements are very high, such as the waviness should be less than 0.1 µm and the surface roughness should be less than 5 nm. However, the surface roughness of the commercially available stainless steel sheet is so large that it can’t meet their requirements of flexible display substrates on surface quality. So, it can’t be used as a flexible substrate directly, otherwise it will affect the performance of flexible display. So, before used, the stainless steel sheet must be ultra precision machined [21]. The lapping is one of the main method in ultra-precision machining for the stainless steel substrate. In the lapping process, it is primarily to reduce or remove surface scratches, reduce the surface roughness, decrease the subsurface damage and improve the flaten of the substrate. So, in following chemical mechanical polishing (CMP) process, the surface quality of the stainless steel substrate after lapped has much influence on the CMP time, the CMP efficiency, the CMP quality and CMP cost. Therefore, the theory, process and technology of ultra-precision lapping for the stainless steel substrate must be studied with high efficiency, high quality and low cost, this will be of great practical significance.

Literatures show that, in the ultra-precision machining of the stainless steel substrate, some researchers have been conducted in-depth study using these machining method, such as grinding, free abrasive lapping and fixed abrasive lapping [22-24] and have gained some abundant research achievements. Under the support of NSFC, our research group have deeply studied the ultra-precision machining of the stainless steel substrates in recent years [25-28]. However, in lapping the stainless steel substrate, some key problems, such as the serious surface and subsurface damage, low lapping efficiency and so on, have not been solved, this will restrict the large-scale production and application. At present, the most urgent problem to be solved is to try to improve the machining efficiency and reduce and eliminate the surface damage in the lapping of the stainless steel substrate.

Tribochemistry is an interplaniemenary subject of chemistry and tribology. It mainly is concerning these studies in the chemical and physicochemical changes of solid surfaces in relative motion under the influence of mechanical energy. The use of mechanical energy to stimulate chemical reactions is one of the oldest experiments in human history. Man has used flint to make fire [29-30]. The tribochemical reaction between two friction surfaces may be caused by friction temperature, catalysis in friction surfaces and mechanical energy. All kinds of physical and chemical effects is directly related to each other relative motion of friction surfaces, and the surface lattice defects and new metal surfaces caused by wear also have catalytic effects on chemical reactions [31-32]. According to literatures, it is found that, in the ultra-precision machining hard and brittle materials, the tribochemical action can cause chemical reaction on friction surface, which can further improve the material removal rate (MRR) and reduce the production cost [33-34]. But now there are no literatures to show the tribochemical mechanical lapping of the stainless steel substrates. Therefore, inspired by this method, took the 304 stainless steel as research object, the method of the tribochemical mechanical lapping has been proposed by our research team to machining the stainless steel substrates.

Research results showed that there are some disadvantages in free abrasive lapping, such as low machining efficiency, serious surface damage, low abrasive utilization ratio and high machining cost [35-36]. So, in this paper, the fixed-abrasive lapping platens with tribochemical reaction were developed, the lapping process with these platens was studied and the most reasonable optimum technological parameters was found. The experimental results were analyzed and some useful conclusions were obtained. In the next step, our research team will focus on these researches of the material removal mechanism and surface morphology and formation on the tribochemical mechanical lapping of the stainless steel substrate.

2 Experimental conditions and methods

Four types of fixed-abrasive lapping platens with tribochemical action under different abrasive sizes were made. The abrasive is white corundum (aluminum trioxide). The fixed-abrasive lapping platens was shown in Figure 1, and then, the fixed-abrasive lapping platens was pasted on aluminum alloy platen by double-sided glue and put on the lapping and polishing machine with the type ZYP230 made by Shenyang, China, shown in Figure 2. Table 1 is the composition and the content of lapping platen [10, 19, 20, 25-28]. The ferric oxide was selected as the oxidant, the stearic acid was selected as the assistant agent, the molybdenum disulfide was selected as the lubricant and the phenolic resins was selected as the binding agent.

| No. | Name | Abrasive size(µm) | Abrasive content(g) | Oxidant content(g) | Assistant agent(g) | Lubricant content(g) | Other |
|-----|------|-----------------|-------------------|-------------------|-------------------|-------------------|-------|

Tab. 1 Composition and content in tribochemical fixed-abrasive lapping platens

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All of the experiments were conducted on the lapping and polishing machine in a super-clean room with cleanliness 1000-grade and temperature controlled at 22°C. Before the experiment, all of the samples, lapped with 600 mesh sandpaper, were prepared to keep the initial conditions of each sample the same. The surface roughness and morphology of each sample were measured by the Contour GT-K white-light interferometer (Vertical resolution 0.01nm) manufactured by BRUKER, USA. The surface condition of each sample was observed by Leica DM2500M metallographic microscope (resolution 1 nm). Using the precision electronic balance (accuracy 0.01mg/80g) of Sartorius CP225D, the MRR was calculated by measuring the quality of the 304 stainless steel before and after lapping.

The orthogonal test parameters as shown in table 2 below are carried out using the four types of tribochemical fixed-abrasive lapping platens.

| Factor          | A    | B    | C    | D    |
|-----------------|------|------|------|------|
| Abrasive size   | Lapping pressure | Lapping time | Lapping speed |
|                 |      |      |      |      |

**Tab. 2 Selection of Orthogonal Test Parameters**
3 Experimental results and analysis

This experiment has 4 factors and 4 levels, thus 16 groups of orthogonal test tables are selected. The orthogonal test results are shown in the Table 3.

| No. | A   | B     | C   | D     | Material removal rate, MRR(nm/min) | Surface roughness, Ra(nm) |
|-----|-----|-------|-----|-------|------------------------------------|---------------------------|
| 1   | 0.5 | 6.895 | 15  | 30    | 43.682                             | 91.659                    |
| 2   | 0.5 | 13.790| 30  | 50    | 53.413                             | 111.955                   |
| 3   | 0.5 | 20.685| 45  | 70    | 88.381                             | 117.404                   |
| 4   | 0.5 | 27.580| 60  | 90    | 102.795                            | 123.404                   |
| 5   | 3.5 | 6.895 | 30  | 70    | 129.365                            | 125.284                   |
| 6   | 3.5 | 13.790| 15  | 90    | 146.286                            | 137.043                   |
| 7   | 3.5 | 20.685| 60  | 30    | 117.062                            | 136.128                   |
| 8   | 3.5 | 27.580| 45  | 50    | 158.062                            | 138.431                   |
| 9   | 7   | 6.895 | 45  | 90    | 167.054                            | 137.795                   |
| 10  | 7   | 13.790| 60  | 70    | 168.436                            | 129.018                   |
| 11  | 7   | 20.685| 15  | 50    | 189.361                            | 147.151                   |
| 12  | 7   | 27.580| 30  | 30    | 202.353                            | 158.383                   |
| 13  | 14  | 6.895 | 60  | 50    | 237.337                            | 184.227                   |
| 14  | 14  | 13.790| 45  | 30    | 243.131                            | 187.601                   |
| 15  | 14  | 20.685| 30  | 90    | 294.543                            | 201.725                   |
| 16  | 14  | 27.580| 15  | 70    | 306.385                            | 226.938                   |

Firstly, the ANOR and calculation of each factor in each index were carried out respectively, and then the analysis results of each index were balanced comprehensively to obtain the optimal test plan.

The calculation results of factor A with each level are as follows.

- \( K(A,1) = 43.682 + 53.413 + 88.381 + 102.795 = 288.271 \)
- \( K(A,1)p = \frac{K(A,1)}{4} = 72.0677 \)
- \( K(A,2) = 129.365 + 146.286 + 117.062 + 158.062 = 550.775 \)
- \( K(A,2)p = \frac{K(A,2)}{4} = 137.6937 \)
- \( K(A,3) = 167.054 + 168.436 + 189.361 + 202.353 = 727.204 \)
- \( K(A,3)p = \frac{K(A,3)}{4} = 181.801 \)
- \( K(A,4) = 237.337 + 243.131 + 294.543 + 306.385 = 1081.369 \)
- \( K(A,4)p = \frac{K(A,4)}{4} = 270.349 \)

Similarly, \( K(B,j) \), \( K(C,j) \), \( K(D,j) \), \( K(B,j)p \), \( K(C,j)p \) and \( K(D,j)p \) can be obtained. Where \( i \) represents the factor, here \( i = A, B, C, D \). \( j \) represents the level, here \( j = 1, 2, 3, 4 \). \( K \) represents the index of material removal rate, \( K(i,j) \) represents the MRR sum in level \( j \) at factor \( i \), \( K(i,j)p \) represents the average values of MRR in level \( j \) at factor \( i \). \( K/ \) represents the index of surface roughness, \( K/(i,j) \) represents the surface roughness sum in level \( j \) at factor \( i \), \( K/(i,j)p \) represents the average values of surface roughness in level \( j \) at factor \( i \). Table 4 shows these calculation results of the orthogonal test.

| Index | A    | B         | C         | D         |
|-------|------|-----------|-----------|-----------|
| K[i, 1]p | 72.0677 | 144.3595 | 171.4285 | 151.5570 |
| K[i, 2]p | 137.6937 | 152.8165 | 169.9185 | 159.5432 |
| K[i, 3]p | 181.8010 | 172.3376 | 164.1570 | 173.1417 |
| K[i, 4]p | 270.3490 | 192.3987 | 156.4075 | 177.6695 |
| ΔRi     | 198.2812 | 48.03925 | 15.0210  | 26.1125  |
In this paper, the surface roughness and the MRR were mainly studied, because they are the better judge to the lapping quality or lapping effect. So, by the value \( K(i, j)p \), the degree of influence for each factor on MRR can be found, by the value \( K/(i, j)p \), the degree of influence from every factor on the surface roughness also can be obtained. The \( \Delta R_i \) and \( \Delta R_i/I \) represent the different of the average values of MRR and surface roughness in factor \( i \), respectively. By the \( \Delta R_i \) and \( \Delta R_i/I \), the degree of influence for each factor on surface roughness and MRR also can be found [37-38]. By comparing the \( \Delta R_i \) or \( \Delta R_i/I \), if the value of \( \Delta R_i \) or \( \Delta R_i/I \) is large, it shows that this factor \( i \) has a greater impact on lapping quality or lapping effect, vice versa. According to the test results in Table 4, the relationship between the factors and the levels of \( K \) and \( K/\)values is drawn, as shown in Figure 3 and Figure 4.

| \( K/(i, 1)p \)  | 111.1055 | 152.7412 | 140.6977 | 143.4427 |
|------------------|----------|----------|----------|----------|
| \( K/(i, 2)p \)  | 134.2215 | 141.4042 | 145.3367 | 145.4410 |
| \( K/(i, 3)p \)  | 143.0867 | 150.6020 | 146.3077 | 150.6610 |
| \( K/(i, 4)p \)  | 200.1227 | 151.7890 | 147.1942 | 159.9917 |
| \( \Delta R/i \)  | 89.0172  | 10.5958  | 6.4965   | 16.549   |

![Fig. 3](image1.png)  
**Fig. 3** Effects of various factors on material removal rate

![Fig. 4](image2.png)  
**Fig. 4** Effects of various factors on surface roughness

By above figures and tables, the analysis result is that the effect orders of each factor on the surface roughness and the MRR are shown as follows. Fig.3 is the influence degree of each factor on the material removal rate. By the Fig.3, it can be found that the change of abrasive size has a great influence on MRR, when the abrasive size increases from 0.5µm to 14µm, the
material removal rate increases from 72nm/min to 270nm/min. The influence degree of other factors is small. So, according to the variation range of the results, the influence degree on the MRR can be determined, it is A>B>D>C. Fig. 4 is the influence degree of each factor on the surface roughness. By the Fig.4, the analysis method is the same as that in Fig. 3, it can be obtained that the degree of influence on the surface roughness is A>D>B>C. From the above orders, Fig.3 and the Fig.4, it can be seen that the size of abrasives has the largest influence on the surface roughness and the MRR in lapping 304 stainless steel with tribochemical fixed-abrasive lapping platen. All of the surface roughness and the MRR increases with the increase of abrasive size. Lapping time has little effect on the surface roughness and the MRR. Influences are that the MRR decreases slowly and the surface roughness increases slightly with the increase of lapping time. The influence on the surface roughness and the MRR, the rotational speed of the lapping platen is different with the lapping pressure. The surface roughness and the MRR increase gradually with the increase of rotational speed of the lapping platen, but with the increase of lapping pressure, the MRR increases gradually and the surface roughness decreases first and then increases. Due to the tribochemical action, there may be an optimal pressure to optimize the interaction between tribochemical action and abrasive removal and maximize the material removal rate.

According to the trend reflected in the chart and table, in order to get a larger MRR, the combination of factors is selected the A4B4C1D4, that is, when abrasive size is 28µm, lapping time is 15 minutes, rotational speed of lapping platen is 90r/min and lapping pressure is 27.580 KPa, the maximum MRR is 412.524 nm/min after lapping experiment. For the reason that the lower surface roughness, the combination of factors is selected the A1B2C1D1, that is, when the abrasive size is 0.5µm, the rotational speed of lapping platen is 15 r/min, the lapping pressure is 13.790 KPa and the lapping time is 15 minutes, the surface roughness drops to 41nm after lapping experiment.

4 Discussion

4.1 Influence of abrasive size on surface roughness and MRR

Because the stainless steel material belongs to the plastic material, in lapping, the material removal is mainly caused by the compound action of the extrusion, the scratching and ploughing produced by abrasives and the lapping platen on the workpiece surface. The removal of surface material belongs to two-body wear [39-40].

By these research results above mentioned, the MRR is in proportion to the rotational speed of the lapping platen and the abrasive size, and in proportion to the lapping pressure P or $P^{1/3}$ or $P^{2/3}$ [41-42].

By the research result of Li [43], the surface roughness is directly proportional to the abrasive size and the lapping pressure $P^{1/3}$, and Yeruva [44] also considered that the surface roughness is directly proportional to the abrasive size and the lapping pressure $P^{2/3}$.

Other researchers also think that with the increase of abrasive size, the surface roughness of workpiece increases exponentially [45-47].

In a word, a certain normal pressure will be loaded during the lapping process. When the quality of each abrasive is equal in fixed abrasive lapping platen, the number of abrasives contained in the lapping platen per unit mass decreases with the enlarge of the abrasive size, but the pressure loaded on a single abrasive increase with the decrease of the number of abrasive. So, the extrusion effect, the scratching action of one abrasive on the surface of workpiece is large, and this will lead to the increase of the cutting force and the cutting ability of abrasive, and cause the MRR increase. At the same time, the depth of the abrasive embedded into the workpiece surface and the length of the contact arc with the workpiece surface of the abrasive increase with the enlarge the abrasive size, and this will lead to the greater of the surface roughness [48]. Under the same normal pressure, when the abrasive size changes smaller, the number of abrasives contained in the unit mass lapping platen will increase and the number of effective abrasives actually involved in the lapping process will also increase. This will lead to the more uniform of the cutting effect, the lower of the surface roughness on the material surface is and the better of the surface quality.

4.2 Influence of lapping pressure on surface roughness and MRR

According to Section 4.1, the lapping process of the workpiece mainly depends on the scratching and cutting effect of the abrasive fixed on the lapping platen. When other parameters are unchanged, the smaller the normal pressure is, the smaller the cutting force of the abrasive on the workpiece is, the smaller the depth of a single abrasive embedded in the workpiece is, and the lower the surface roughness and the MRR are. When the lapping pressure increases, the pressure on the working abrasives increases, and the depth of abrasives pressed into the workpiece surface increases, therefore, the ploughing effect of abrasives on the workpiece surface increases, and the MRR increases [49]. In addition, with the increase of the lapping pressure, the friction force between the workpiece and
the lapping platen increases, and the friction chemical reaction can increase, which also can promote the MRR. Therefore, the MRR and surface roughness increase with the increase of lapping pressure. This conclusion is consistent with the research results of literatures.

4.3 Influence of lapping platen speed on MRR and surface roughness

According to Section 4.1, when the normal lapping pressure is not changed, the cutting force of the abrasive on the workpiece is not changed. The lower the rotational speed of the lapping platen is, the shorter the contact length of the single abrasive on the workpiece surface in unit time is, and the shorter the scratch length of the total abrasives on the workpiece surface is, so the lower the MRR is. With the increase of the rotation speed of the lapping platen, the contact times between single abrasive and workpiece surface increase, the cutting path length of the total abrasives increases, so, the MRR increases. But, when the normal lapping pressure is constant, the cutting force and cutting depth of the abrasive is constant basically, so the rotation speed of lapping platen has less influence on the surface roughness.

4.4 Influence of lapping time on surface roughness and MRR

In the lapping process, with the increase of lapping time, most abrasives on the lapping platen become gradually blunt and the cutting ability of the abrasive is reduced, which will result in the decrease of MRR. In addition, with the increase of lapping time, on the surface of the lapping platen, the lapping waste and debris accumulated increase, which may participate in the lapping, this will affect the normal process of lapping and lead to the larger of surface roughness. This is the reason that the lapping platen must be conditioned after lapping for a certain time.

5 Conclusion

In this paper, the surface roughness and the MRR were mainly studied by lapping the 304 stainless steel using the tribochemical fixed-abrasive lapping platen developed by our research group. The conclusions are as follows. The influence degree on the MRR from better to worse is the abrasive size, the lapping pressure, the rotation speed of lapping platen and the lapping time. The influence degree on the surface roughness from better to worse is the abrasive size, the rotation speed of the lapping platen, the lapping pressure and the lapping time.

In lapping process, the material removal of the 304 stainless steel is mainly caused by the compound action of the extrusion, the scratching and ploughing produced by abrasives of the tribochemical fixed-abrasive lapping platen. The abrasive size has the greatest influence on the surface roughness and the MRR, and the MRR and surface roughness increase with the increase of abrasive size. Lapping time has less effect on lapping results. The surface roughness increases slightly and the MRR decreases slowly with the increase of lapping time.

When the lapping pressure increases, the mechanical action of abrasives increases, and then, the surface roughness and the MRR increase. When the increase of the rotation speed of the lapping platen, the cutting path length of the total abrasives increases, so the MRR increases, but the rotation speed of lapping platen has less effect on the surface roughness.

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