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DEVELOPMENT OF INTELLIGENT LAPPING SYSTEM ESTIMATION OF FINISHED SURFACE ROUGHNESS AND ITS IMPROVEMENT SPEED

The lapping process is one of the traditional finishing processes and generally it is conducted as manual process by skilled worker. The productivity of these manual processes is lower and difficult to control. Hence, we developed an automatic lapping system for moulds and dies. The lapping system consists of simple lapping tools and conventional milling machine. Several materials were machined as mirror like surface using the system. The lapping conditions are usually decided by skilled worker's experience or knowhow. Therefore, in this study, an intelligent lapping system with the optimum conditions calculated by the lapping model was developed. Specifically, the relationship between the finished quality (surface roughness *Rz* and improvement rate of *Rz*) and each parameter of the system, Vickers hardness of work piece and lapping head, lapping pressure, grain size, is investigated. Then, an intelligent lapping system is developed. Finally, the HPM31 are machined as confirmatory experiment by developed system with calculated lapping conditions. It is concluded from the result that: (1) The relationship between the surface roughness and lapping parameter was cleared. (2) The intelligent lapping system using the lapping model was developed. (3) The estimated limit surface roughness and improvement rate by calculated condition satisfactorily agreed with the experimental results.

1. INTRODUCTION

The abrasive machining such as lapping or polishing is conducted for the finishing of moulds and dies as manual process by skilled worker. And these manual processings are one of the factors of low productivity. Recently, the alternate techniques for them are researched (1), (3), (4), (6), (8). However, generally these techniques need a special and expensive system. Therefore, simple lapping system using the cheep lapping tool and conventional

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CNC milling machine was developed (2). The developed lapping system needs the several pre-experiments for deciding the optimum conditions. This study aimed the estimation of the optimum lapping conditions without experiments. The relationships between the parameters of the lapping system and the finished quality (surface roughness Rz and its improvement rate) are researched. An intelligent lapping system is developed with these relationships. Finally, the developed system is evaluated by confirmatory experiment.

2. DEVELOPED AUTOMATIC LAPPING SYSTEM FOR MOULDS AND DIES

The schematic view of the developed lapping system in previous study is shown in Fig. 1. A lapping tool consists of tool head and the spring for controlling the lapping pressure. The tool is attached to the conventional CNC milling machine. The work piece is lapped by the slide motion of tool head with lapping pressure. Lapping is conducted in the vessel filled with lapping slurry. The tool is moving with reciprocating motion for cleaning and dressing. As the spring with small spring constant is used, the positioning accuracy of the CNC milling machine makes lesser effect on finished surface roughness. Then this system is capable of good finishing even conventional CNC milling machine is used.

3. WORSE OF DIMENSIONAL ACCRACY AND SIZE

An example of the improvement of surface roughness regarding to the grain size using the lapping system with each grain is shown in Fig. 2. On the lapping process, the limit surface roughness is seemed on each grain size. If lapping is continued after approaching thelimit surface roughness, the dimensional accuracy become worse. This is most obvious in lapping with large grain. Photographs of the excess lapped mould for the sintered lack gear is shown in Fig. 3. Material of work piece is cemented carbide (V20, HV=1900). The shape

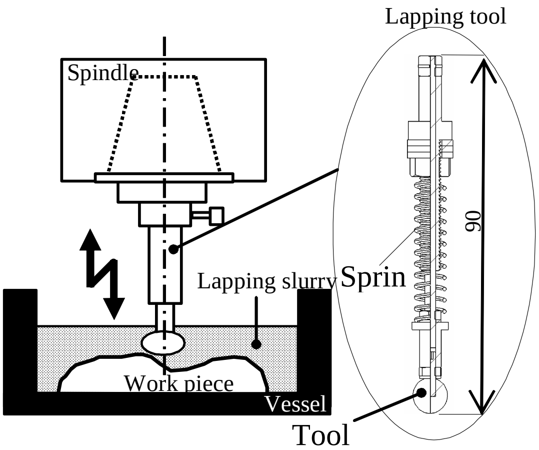


Fig.1. Schematic view of developed lapping system

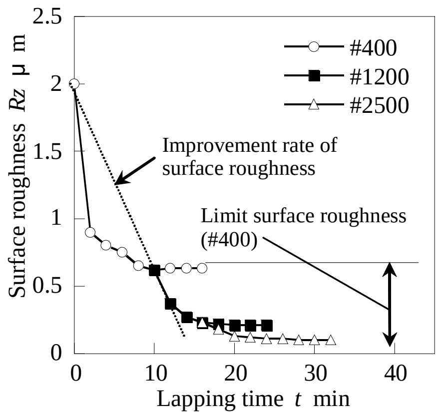


Fig. 2. Example of improvement curve of surface roughness (improvement rate and limit of surface roughness)

of the gear becomes worse due to the excess lapping after the limit surface roughness. The relationship between the improvement of the surface roughness and worse of the dimensional accuracy is shown in Fig. 4. After the start of machining, surface roughness is improved until 20 min. After that, only dimensional accuracy of the gear become worse.

Then, the dimensional accracy become easily worse even high stiffness material as V20. Hence, estimation of the limit surface roughness Rz_{lim} and improvement of the surface roughness is necessary to prevent the excess lapping.

4. ESTIMATION OF LIMIT SURFACE ROUGHNESS BY LAPPING THEORY

Sato et al.,(7) researched about the lapping theory using Vickers hardness. The theoretical limit surface roughness Rz_{lim} is followed as Eq.1. The work piece is defined as perfectly plastic body in Eq.1. The depth of indentation by the grain directly affects the surface roughness.

$$Rz_{\mathrm{lim}} = 0.768 \frac{1}{\tan \alpha} \left(\frac{P}{HV_{\mathrm{work}} N_{\mathrm{e}}} \right)^{\frac{1}{2}} \tag{1}$$

Where, Rz_{lim} is limit surface roughness [μm], P is lapping force [N], α is angle of tip of the grain [degree], HV_{work} is Vickers hardness of the work piece and N_{e} is effective number of grain. In the case of histogram of the grain has normal distribution, N_{e} is calculated by Eq.2.

$$N_{\mathrm{e}} = 0.09\pi \frac{P \left(HV_{\mathrm{work}}^{-\frac{1}{2}} + HV_{\mathrm{head}}^{-\frac{1}{2}} \right)^2}{\tan^2 \alpha \; X_1 \left(1 - \dfrac{X}{X_1} \right)} \tag{2}$$

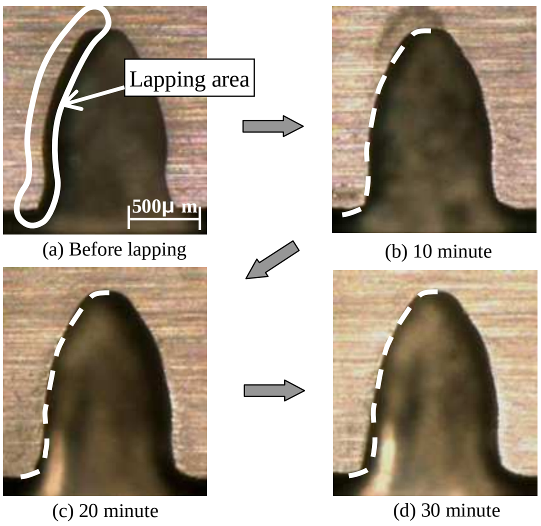


Fig. 3. Photographs of lapped gear mould. The form accuracy become worth by excess lapping.

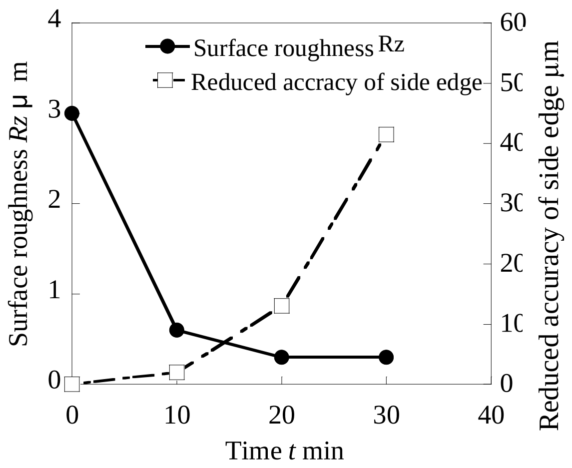
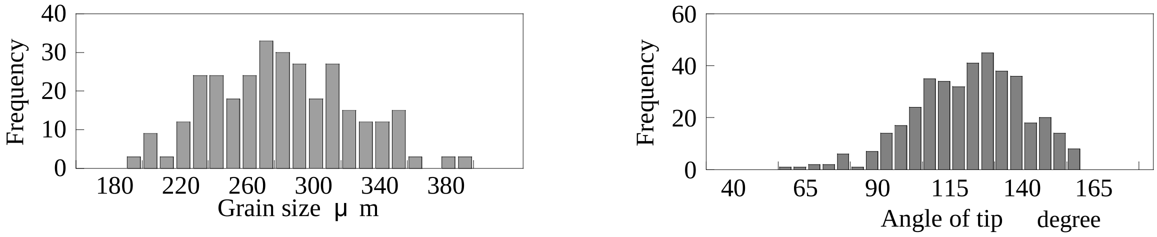


Fig. 4. Relationship between the improvement of surface roughness and the dimensional accuracy regarding to lapping time.

Where, HV_{head} is Vickers hardness of the lapping tool head, X_l is maximum size of the grain and X is average size of the grain. The limit surface roughness becomes possible to be calculated with each lapping condition by measurement data of the grain (standard division of histogram and average size). The example of the measured results of diamond grain(#120) is shown in Fig. 5. Both the grain size and the angle of the tip have normal distribution. And the angle of the tip does not depend on the grain size. The measured results of several size of grain were shown in Table 1. The calculated results using Eq.1 and the experimental results were shown in Fig. 6. The calculated values can estimate the experimental results well and its error is less than 25%.

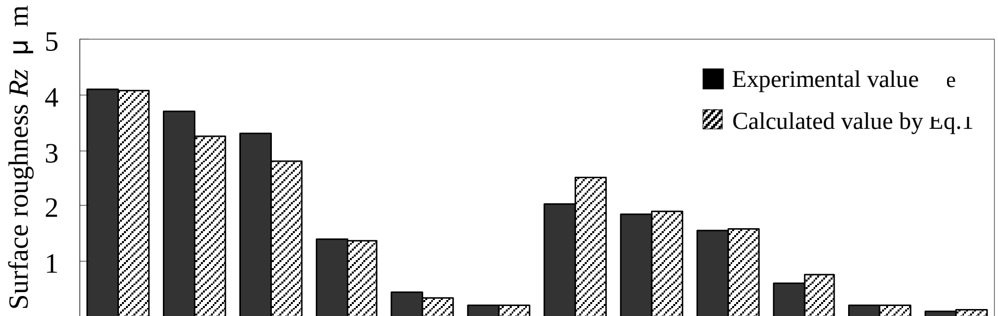


(a) Histogram of grain size (#120) (b) Histogram of Angle of tip (#120)

Fig. 5. Measurement results of variation regarding to grain size and angle of tip (#120)

Table 1. Measured results of each grain size and angle of tip

Mesh of grain	Average grain size μm	Standard division μm	Average angle of tip degree
#120	287.9	48.7	122.9
#400	48.8	8.4	118.3
#1200	15.8	2.8	116.7
#2500	11.0	2.1	114.1



Condition No.		1	2	3	4	5	6	7	8	9	10	11	12
Material of work piece		SKD61						V10					
HV of work piece		500						2200					
Material of lapping head		Steel	Nylon	PP	PP	PP	PP	Steel	Nylon	PP	PP	PP	PP
HV of lapping head		290	14	9	9	9	9	290	14	9	9	9	9
Lapping pressure MPa		50	50	25	25	25	25	50	50	50	50	50	50
Grain size		#120	#120	#120	#400	#1200	#2500	#120	#120	#120	#400	#1200	#2500
Surface roughnes	Experimental value	4.09	3.70	3.30	1.40	0.44	0.21	2.04	1.86	1.56	0.60	0.21	0.11
	Calcurated value	4.06	3.25	2.80	1.37	0.35	0.22	2.50	1.89	1.58	0.77	0.20	0.12
Error %		0.6	13.7	17.8	2.1	24.8	2.8	18.7	1.7	1.4	22.5	5.5	15.1

Fig. 6. Compared result of limit surface roughness both experimental value and calculated value with each lapping conditions

5. ESTIMATION OF IMPROVEMNET CURVE OF SURFACE ROUGHNESS

The improvement rate of surface roughness is easily calculated theoretically if principle of the lapping is only the cutting by the grain. However, it is not only the cutting but also plastic deformation, wearing and chemical reaction. Xiaobin (9) et al., experimentally researched about the relationship between the removal volume of the work piece and the lapping time. And it was cleared that the removal volume of the lapping is not constant and reducing with lapping time. Then, generally the relationship between the surface roughness and the machining time express first order lag curve. The improvement of the surface roughness is followed as Eq.3 using the general formula of first order lag.

$$Rz = Rz_{\mathrm{ini}} - (Rz_{\mathrm{ini}} - Rz_{\mathrm{lim}})(1 - e^{-\frac{t}{T}}) \tag{3}$$

Where, Rz is surface roughness of the work piece, Rz_{ini} is the initial surface roughness before lapping, Rz_{lim} is the limit surface roughness, t is machining time and T is the time constant of response curve. The initial surface roughness is cleared by the measurement and the limit surface roughness Rz_{lim} can be calculated by Eq.1 and Eq.2. Therefore, improvement rate of surface roughness is expressed if estimation of the time constant is possible. The time constant is directly proportional to work area and inversely proportional to feed pitch and lapping speed. Moreover, processing time till reach to the limit surface roughness is increased when the initial surface roughness Rz_{ini} is higher or the limit surface roughness Rz_{lim} is lower. Then, the time constant T is considered as a function of these parameters and its relation is investigated by experiment. The experimental conditions are decided as Rz_{lim} became 0.15, 0.3 and 0.8 μm. The relationship between the time constant T and the initial surface roughness Rz_{ini} regarding to limit surface roughness is cleared and shown in Fig. 7. It is seemed the relationship between the initial surface roughness Rz_{ini}

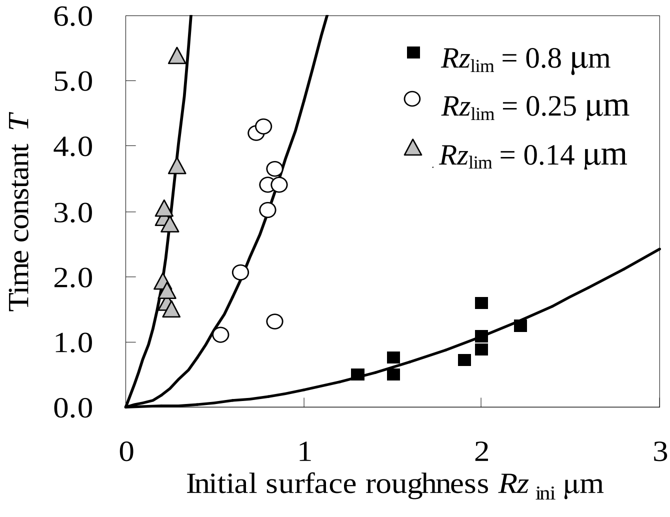


Fig. 7. Relationship between time constant T and initial surface roughness Rz_{ini} regarding to Rz_{lim}

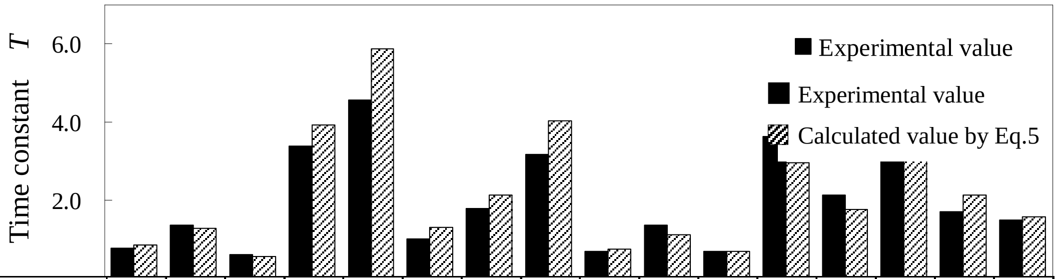
and the time constant T takes the exponent function. The time constant T becomes large when the limit surface roughness Rz_{lim} becomes small, and is expressed as Eq.4 using the lapping parameters.

$$T = C\frac{ARz_{\mathrm{ini}}^{\mathrm{m}}}{pvRz_{\mathrm{lim}}^{\mathrm{n}}} \tag{4}$$

Where, A is work area [mm^2], p is pitch [mm], v is lapping speed [mm/min], and C, m, n are constant value. In the Eq.4, although other parameters (lapping pressure, grain size and so on) are not regarded, these are already considered in the estimation of the limit surface roughness Rz_{lim}. Hence, Eq.4 can be considered as the model regarding to all lapping parameters. Next, regression analysis method is used to results in Fig. 7 for deciding the constant value in Eq.4. Then, experimental model is obtained as Eq.5.

$$T = 0.343\frac{ARz_{\mathrm{ini}}^{1.99}}{pvRz_{\mathrm{lim}}^{2.87}} \tag{5}$$

The process time for limit surface roughness is similar to triplication of the time constant T. Although the Eq.5 is the experimental model, the estimation accuracy is good and its error were less than around 20%. Several of the compared results for the calculated time constant and experimental one is shown in Fig. 8.



Condition No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Rz_{ini} μm		2	2	2.21	0.8	0.8	0.65	0.23	0.23	2	2	2.1	0.84	0.63	0.29	0.26	0.22
Rz_{lim} from Eq.1 μm		0.8	0.8	0.78	0.25	0.25	0.25	0.13	0.12	0.84	0.84	0.7	0.29	0.22	0.13	0.14	0.11
Material of work piece		2.0	2.0	G5						2.0	2.0	SKD61					
Grain size		400			1200			2500		400			1200		2500		
Lapping pressure MPa		5	25	50	5	25	50	5	25	5	25	50	5	50	5	25	50
Lapping speed mm/min		3000	#2000	3000	3000#	2000	3000	3#00	2000	3000#	2000	3000	3#00	3000	3000#	3000	3000
Pitch mm		0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.2
Lapping area mm^2		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Time constant	Experimental value	0.77	1.35	0.63	3.40	4.56	1.03	1.80	3.19	0.70	1.35	0.70	3.64	2.15	3.70	1.70	1.51
	Calculated value	0.86	1.29	0.57	3.92	5.88	1.30	2.14	4.04	0.75	1.12	0.70	2.97	1.76	3.01	2.13	1.58
Error %		10.6	4.4	11.0	13.2	22.4	20.9	16.0	21.1	6.5	20.1	0.5	22.7	22.2	22.9	20.0	4.9

Fig. 8. Compared result of time constant T both the experimental value and calculated value with each lapping conditions

6. EVALUATION OF THE LAPPING MODEL BY CONFIRMATORY EXPERIMENT

In this chapter, obtained lapping model and developed intelligent lapping system is evaluated by experiment. HPM31(HV400, Rz_{ini}=2.0 μm) is used as material of work piece. The mirror-like finishing is conducted using the lapping system. The lapping conditions and estimated results from the condition are followed on Table 2. The conditions are decided from the relationship of Eq.1 and Eq.5. The work area is square surface and its area is 100mm^2. The PP ball (φ 9.6 mm) is used as lapping head. The relationship between the machining time and the surface roughness is shown in Fig. 9. The calculated improvement curve is drawn by the solid line until the estimated replacement timing in Table 2.

Table 2. Lapping conditions and calculated values for confirmatory experiment of estimation method of Rz_{lim} and T

Material of work piece	HPM31 (HV=400)		
Surface roughness before lapping Rz_{ini} μm	2.0 (EDM finished)		
Lapping head	Polypropylen (HV=9.0)		
Lapping pressure MPa	30		
Pitch mm	0.1		
Lapping speed mm/min	3000		
Grain size	#400	#1200	#2500
Effective number of grain estimate N_e	28	223	816
Limit surface roughness estimate Rz_{lim} μm	0.73	0.25	0.13
Time constant estimate T	0.89	2.62	4.67
Replacement timing of the grain min (= T×3.0)	2.67	7.86	14.01

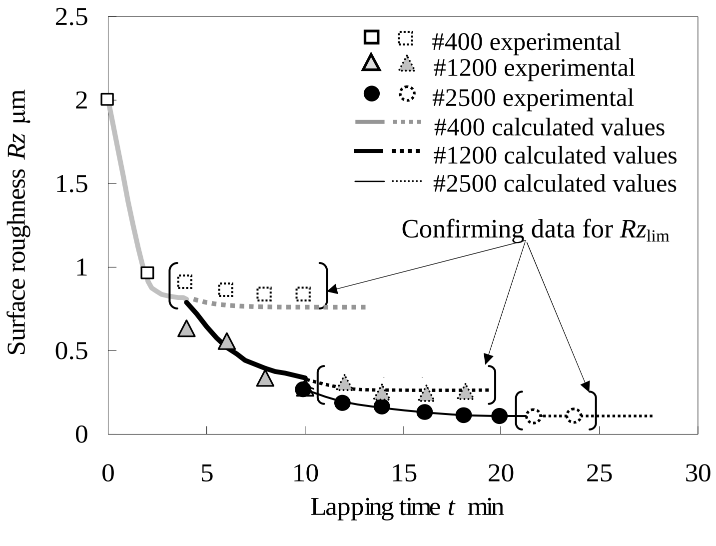


Fig. 9. Result of calculated T and Rz_{lim} compared with experimental result

The dotted lines show the calculated surface roughness after the timing, and finally the surface roughness approaches the limit surface roughness Rz_{lim}. The measured data by experiments were plotted as points. The confirming data by experiment for estimation of Rz_{lim} were also plotted in Fig. 9. The calculated value is capable of the experimental data, and its estimation error was lower than 15%. Then, the work piece is finally finished to mirror-like surface with 0.12 μmRz. The calculated time constant also has good estimation accuracy and its error is less than 20%.

7. CONCLUSIONS

It is concluded from the result that: (1) The developed lapping system and proposed lapping model is effective to estimate the improvement of surface roughness. (2) The worse of geometrical accuracy by excess lapping is prevented using the intelligent lapping system.

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