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Effects of the Grinding Conditions on the Machining Elasticity Parameter

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ABSTRACT

The grinding force generated during the grinding process causes an elastic deformation of the workpiece, grinding wheel, and machine system. Thus, the true depth of cut is always smaller than the apparent depth of cut. This is known as machining elasticity phenomenon. The machining elasticity parameter is defined as a ratio between the true depth of cut and the apparent depth of cut. It is an important factor to understand the material removal mechanism of the grinding process. To increase productivity, the value of this machining elasticity parameter must be large. Therefore, it is essential to know the characteristics of this parameter. The objective of this research is to study the effect of the major grinding conditions, such as table speed, depth of cut, on this parameter experimentally. Through this research, it is found that this parameter value is increasing when the table speed is decreasing or the depth of cut is increasing. Also, this parameter value depends on the grinding mode (up grinding, down grinding).

Key Words : Machining elasticity parameter, Surface grinding, Up grinding, Down grinding, Apparent depth of cut, True depth of cut, Table speed

1. Introduction

The force generated during the conventional material removal processes causes an elastic deformation of the workpiece, grinding wheel, and machine system. This elastic deformation happens in every conventional material removal process. The elastic deformation in turning and milling processes is relatively smaller than that in grinding processes in general. Grinding processes are performed to enhance the accuracy of turned and/or milled parts. Thus, the machining elasticity phenomenon is intimately related on the productivity and accuracy of the ground parts. The threshold grinding force and spark-out operation in grinding process are due to this phenomenon.

From productivity and accuracy points of view, the importance of grinding processes is well recognized. But, optimal grinding conditions are not well established in comparison with the other material removal processes, because of difficulties in in-process observation and modeling of probabilistic characteristics. The grinding conditions are dependent on the experience of the machine operator in real grinding processes. Thus, it is required to understand the machining elasticity phenomenon for the establishment of the optimal grinding conditions. The followings are the results of the previous studies on this area.

The machining elasticity parameter was introduced by Rowe, Barash, and Koenigsberger[1] in their research on the roundness characteristics in centerless grinding firstly. They defined this parameter as a ratio between the true depth of cut and the apparent depth of cut, and showed that this parameter increases when the apparent depth of cut decreases. Wager and Saini[2] studied the behavior of grits after the contact with a workpiece. They found that the real material removal happens when the normal force applied on grit reaches to a certain value. Until then, grit are showing just deformation, rotation,

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and sliding behaviors without any material removal of workpiece. They also revealed that the local contact deformation and the normal force increase when the hardness of workpiece increases. Gu and Wager[3,4] discovered that the ratio between the true contact length and the geometrically calculated contact length is reducing by increasing depth of cut. Through their research, they also showed that the down grinding generates larger grinding force and longer contact length than the up grinding, when the same depth of cut is engaged in each process. The relation between the hardness of grinding wheel and the local elastic deformation has been studied by Saini.[5]

The objective of this study is for understanding the effect of grinding conditions on the machining elasticity parameter. Firstly, this parameter is defined again. Then, the characteristics found in experiments are investigated. Experiments are performed on the surface grinding process. The table speed and depth of cut are selected as grinding variables in experiments.

2. Machining Elasticity

Fig. 1 shows the relationship between grinding force and material removal rate. Even though there is a physical contact between the grinding wheel and workpiece, the material removal does not happen until the normal grinding force reaches to a certain limit value. This limit of the normal grinding force is called a threshold grinding force, and the depth of cut corresponding to the threshold grinding force is called a threshold grinding depth t_d. So, the true depth of cut is always smaller than the apparent depth of cut.

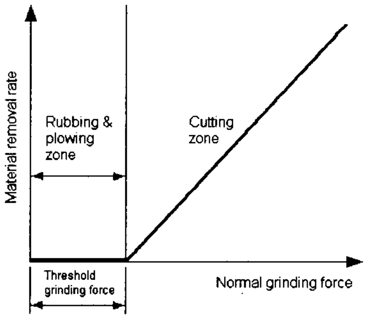

Fig. 1 Relationship between grinding forces and material removal rate

The machining elasticity phenomenon is shown in Fig. 2 schematically. This phenomenon is explainable using a machining elasticity parameter κ. κ is a positive number being less than 1. It has not yet been properly investigated, but been known to be affected by grinding conditions.

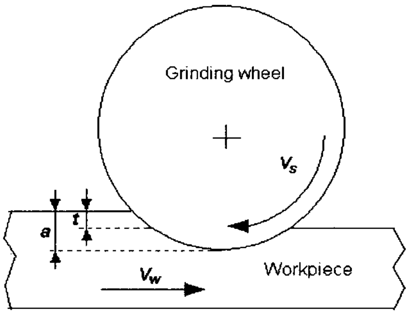

Fig. 2 Illustration of machining elasticity phenomenon

The machining elasticity parameter is defined as a ratio between the true depth of cut t and the apparent depth of cut a. Thus,

$$\kappa = \frac{t}{a} \tag{1}$$

If the initially engaged apparent depth of cut is fixed without any more applied depth of cut all through the process, and the table is traversing repeatedly, the apparent depth of cut at a certain instant is equivalent to the initially engaged apparent depth of cut minus the accumulated true depth of cut till that time. In surface grinding process, the table traversing from the right side to left side and from left side to right side is continued alternatively. So, in every traverse, the apparent depth of cut and the true depth of cut are changing, and the machining elasticity parameter is also changed. Thus, when the number of traverse is i, the machining elasticity parameter is expressed as follows,

$$\kappa_{(1)} = \frac{t_{(1)}}{a_{(1)}} = \frac{t_{(1)}}{a}$$

$$\kappa_{(2)} = \frac{t_{(2)}}{a_{(2)}} = \frac{t_{(2)}}{a(1-\kappa_{(1)})}$$

$$\kappa_{(3)} = \frac{t_{(3)}}{a_{(3)}} = \frac{t_{(3)}}{a(1-\kappa_{(1)})(1-\kappa_{(2)})} \qquad (2)$$

$$\vdots$$

$$\vdots$$

$$\kappa_{(i)} = \frac{t_{(i)}}{a_{(i)}} = \frac{t_{(i)}}{a(1-\kappa_{(1)})(1-\kappa_{(2)})\cdots(1-\kappa_{(i-1)})}$$

where $\kappa_{(i)}$, $t_{(i)}$, and $a_{(i)}$ are the machining elasticity parameter, the true depth of cut, and the apparent depth of cut in the i_{th} traversing of table, respectively.

3. Experiment

The surface grinding machine used in the experiment was WSG-7050A produced by Woojin machinery Co. For more accurate control of the depth of cut, a linear scale with 0.5μm resolution was attached to it. The specification of grinding wheel was WA46K8VIA that is made from vitrified bonded Aluminum-oxide(Al_2O_3) grits. The grit size, grade, and structure of this grinding wheel were in the medium ranges that are the most common and widely used. To maintain the same experimental environments, the grinding wheel surface was dressed twice with 0.01mm depth for each pass just before grinding a specimen, and the coolant flow rate was also kept constant during the experiment.

The specimen was made from a general purpose carbon steel (SM45C), and heat treated by high frequency induction hardening. Before heat treatment, it was prepared as a hexahedron (length: 60mm, height: 20mm, width: 30mm). Especially, the width of the specimen was made to be narrower than that of the grinding wheel for eliminating any cross feed movement. Additionally, to minimize differences in the surface geometry and condition between specimens, the top and bottom surfaces of them were ground before the experiment. For the experimental grinding, the specimen was mounted on the table using a magnetic chuck. Because of the existence of threshold grinding depth, it is very difficult to control the depth of cut accurately. So, before the planned depth of cut was applied, the specimen was ground slightly until no more sparks were generated. Then, the linear scale was set to be zero with no change in the relative distance between the specimen and the grinding wheel, and the planned depth of cut was applied. At the end of each traverse, the table was stopped, and the height of specimen was measured using measurement jigs and a micrometer. From the measurement data, the true depth of cut was calculated. Fig. 3 shows the measurement locations. To increase the reliability of the experiment, six points were selected as measurement locations. Grinding and measurement were performed in process repeatedly until no more sparks were generated. The experimental conditions are shown in Table 1. To reduce the experimental error in results, six specimens were ground for every variable experimental condition.

Table 1 Experiment conditions

Fixed	
grinding wheel	WA46K8VIA
grinding wheel speed (rpm)	1800
dressing depth (mm)	0.01 × 2
Grinding wheel size (O.D. × W mm)	ϕ 305 × 38
Variable	
table speed (m/sec)	0.073, 0.122, 1.163
depth of cut , d (μm)	3, 7, 10

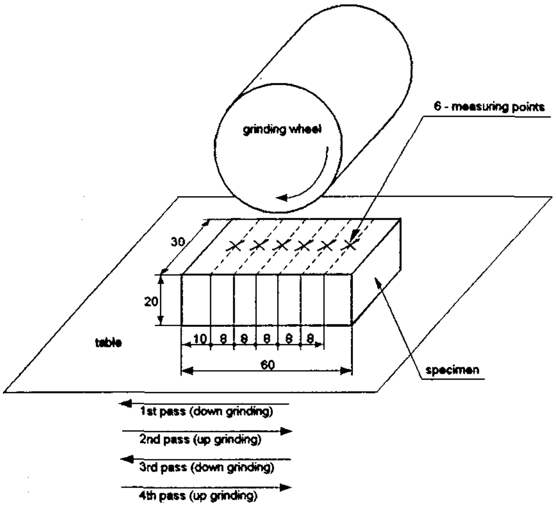

Fig. 3 Schematic diagram of experiment

4. Results and Discussion

4.1 Result

The true depth of cut and machining elasticity parameter are calculated based on the measurement data, and shown in Table 2. The reference of the distance between the specimen and grinding wheel was set on the instant when sparks were disappeared completely. So, even though the linear scale was set to be zero, it is supposed that there was an engagement between the specimen and the grinding wheel at this instant because of the threshold grinding depth. Thus, for the calculation of the machining elasticity parameter, the apparent depth of cut a in equation (2) is considered to be a sum of the applied depth of cut d and the threshold grinding depth t_d. The threshold grinding depth is dependent on the workpiece material and the grinding wheel type. In this study, t_d is assumed as 3.5μm from a reference 6.

Table 2 Experimental results

table speed (m/sec)	applied depth of cut, d (μm)	No. of traver-se	true depth of cut, t (μm)	machining elasticity parameter, κ
0.073	3	1	1.1333	0.1744
		2	0.7667	0.1429
		3	0.8000	0.1739
	7	1	2.6333	0.2508
		2	1.5333	0.1949
		3	1.6667	0.2632
		4	0.7000	0.1500
	10	1	3.8333	0.2840
		2	1.9333	0.2000
		3	2.3667	0.3060
		4	0.6667	0.1242
0.122	3	1	1.1000	0.1692
		2	0.4000	0.0741
		3	0.8000	0.1600
	7	1	2.0000	0.1905
		2	0.8333	0.0980
		3	0.8000	0.1043
		4	0.4333	0.0631
	10	1	2.9333	0.2173
		2	1.5333	0.1451
		3	1.7667	0.1956
		4	0.6333	0.0872
		5	0.5000	0.0754
0.163	3	1	0.9000	0.1385
		2	0.2666	0.0476
		3	0.9000	0.1688
	7	1	2.0000	0.1905
		2	1.0667	0.1255
		3	1.4667	0.1973
		4	0.2333	0.0391
	10	5	0.8333	0.1453
		1	3.1667	0.2346
		2	1.7667	0.1710
		3	1.6667	0.1946
		4	1.0667	0.1546

As found from the experimental results in Table 2, the machining elasticity parameters when the number of traverse is odd numbers are greater than those when the number of traverse is even numbers in most cases. It is already shown in Fig. 3 where the odd and even numbered table traverses mean a down grinding mode and an up grinding mode, respectively. It can be told that the machining elasticity parameter for the down grinding mode is greater than that for the up grinding mode.

It is hard to find any characteristics or trends from these experimental results except the effect of the grinding mode. It seems like that there were some experimental errors. It is presumed that the major source of errors is related to the difficulties in the accurate control of the applied depth of cut. It is inferred from the difference between the applied depth of cut d and the accumulated true depth of cut d_n. As mentioned before, d was engaged just after the disappearance of all sparks, and kept constant all through the process until no sparks were generated any more again. The initially applied depth of cut does not include the threshold grinding depth. So, if the threshold grinding depth is assumed to be constant in the process, the applied depth of cut d must be equal to the accumulated true depth of cut d_n theoretically. But, as shown in Table 3, d_n is always less than d in all cases. And, the differences, d- d_n, are not small enough to be ignored.

Table 3 Accumulated true depth of cut

table speed (m/sec)	accumulated depth of cut, d_n (μm)	standard deviation	d_n - d (μm)
0.073	2.7	0.7583	0.3
	6.5	1.1081	0.5
	8.8	1.4832	1.2
0.122	2.3	0.4625	0.7
	4.0	0.8944	3.0
	7.4	0.6055	2.6
0.163	2.1	0.2528	0.9
	4.8	0.5963	2.2
	7.7	0.9930	2.3

4.2 Revised result

To compensate the errors, the apparent depth of cut a is regarded as a sum of the accumulated true depth of cut d_n and the threshold grinding depth t_d. Then, the machining elasticity parameter κ is re-calculated.

Revised experimental results are provided in Table 4.

Table 4 Revised experimental results

table speed (m/sec)	accumulated true depth of cut, d_n (μm)	No. of traverse	average machining elasticity parameter, κ	standard deviation
0.073	3	1	0.1757	0.05
		2	0.1472	0.02
		3	0.1799	0.03
	7	1	0.2628	0.02
		2	0.2069	0.02
		3	0.2807	0.04
		4	0.1617	0.07
	10	1	0.3104	0.03
		2	0.2272	0.02
		3	0.3571	0.07
		4	0.1565	0.06
0.122	3	1	0.1905	0.02
		2	0.1193	0.06
		3	0.1908	0.03
	7	1	0.2526	0.02
		2	0.1395	0.02
		3	0.1565	0.04
		4	0.0967	0.06
	10	1	0.2625	0.04
		2	0.1869	0.06
		3	0.2623	0.07
		4	0.1302	0.08
0.163	3	1	0.1569	0.01
		2	0.0515	0.05
		3	0.1976	0.04
	7	1	0.2165	0.02
		2	0.1463	0.01
		3	0.2330	0.04
		4	0.0470	0.03
	10	1	0.2672	0.03
		2	0.2054	0.03
		3	0.2414	0.02
		4	0.2059	0.02

As expected, the revised experimental results reveal more information than the experimental results. The changes of the accumulated depth of cut for each table traverse are presented in Fig. 4. There are increasing trends of the accumulated depth of cut when the applied depth of cut and the number of traverse increase. Fig. 5 shows the relationship between the table speed and the accumulated true depth of cut. From this figure, it is found that the accumulated true depth of cut decreases when the table speed increases.

The changes of the machining elasticity parameter for each table traverse are shown in Figs. 6 and 7. Fig. 6 is for the cases of the constant table speed, and Fig. 7 is for the cases of the constant applied depth of cut. Because of the experimental errors, it is not easy to suggest any relevance between the machining elasticity parameter and the grinding variables in these figures. But, through the simultaneous consideration on the trend in Fig. 5 and the information in Fig. 7, it can be told that there is an inversely proportional relation between the table speed and the machining elasticity parameter.

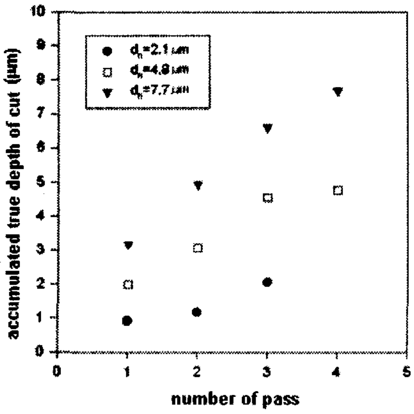

Fig. 4 Accumulated true depth of cut (V_w = 0.163m/sec)

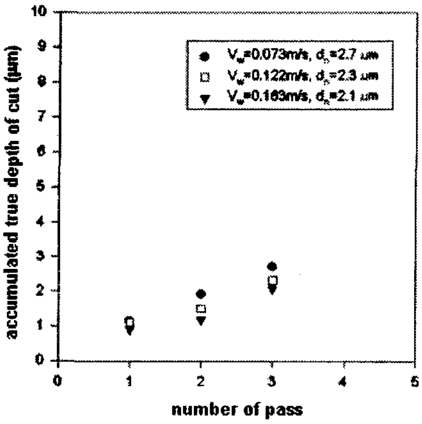

Fig. 5 Accumulated true depth of cut (d = 3.0μm)

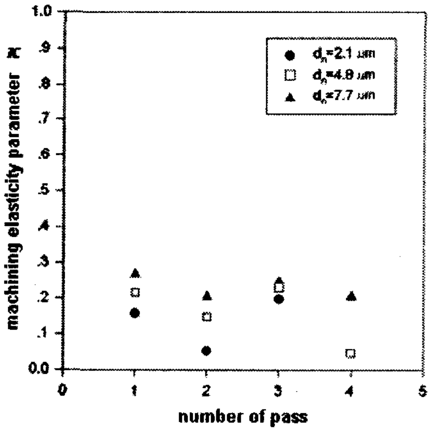

Fig. 6 Machining elasticity parameter (V_w = 0.163m/sec)

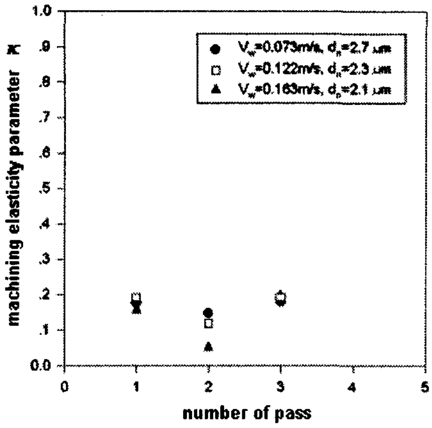

Fig. 7 Machining elasticity parameter (d = 3.0μm)

The data points in Figs. 6 and 7 move up and down alternatively. From this, it can be seen more clearly that there is an intimate relation between the machining elasticity parameter and the grinding mode. If the apparent depth of cut is constant, the down grinding has higher normal grinding force and longer contact length in comparison with the up grinding in general. And, the higher normal grinding force and longer contact length mean that more materials are removed in the process.

4.3 Discussion

The value of the machining elasticity parameter in this study is relatively much greater than that in Rowe, Barash, and Koenigsberger's research. It is supposed that this difference is caused from the difference in the grinding processes themselves. They studied the centerless grinding process, in which a workpiece is supported by a work-rest blade only. But, the workiece in the surface grinding process, which is experimented in this study, is held on the table rigidly. Thus, if the applied depth of cut for each process is equal, the surface grinding system, of which rigidity is relatively high, shows relatively small elastic deformation, and has relatively deep true depth of cut in comparison with the centerless grinding. So, the machining elasticity parameter in relatively rigid system is greater than that in relatively pliable system.

5. Conclusions

The effects of grinding conditions on the machining elasticity parameter in the surface grinding process were investigated experimentally. The table speed and the depth of cut, being easy to be controlled by an operator in process, were selected as major grinding variables. The followings are the results of this study.

- The machining elasticity parameter for the down grinding mode is greater than that for the up grinding mode.
- The machining elasticity parameter decreases when the table speed increases.
- The machining elasticity parameter increases when the depth of cut increases.

Through the comparison of this study with the previous research results, it was also found that the rigidity of the material removal system has strong relationship with the machining elasticity parameter.

References

1. Rowe, W. B., Barash, M. M. and Koenigsberger, F., "Some Roundness Characteristics of Centerless Grinding," Mach. Tool Des. Res, Vol. 5, pp. 203~215, 1965.
2. Wager, J. G. and Saini, D. P., "Local Contact Deflections in Grinding-Groups of Grains and Single Grains," Annals of the CIRP, Vol. 35/1, pp. 245~248, 1986.
3. Gu, D. Y. and Wager, J. G., "New Evidence on the Contact Zone in Grinding - Contact Length, Sliding and Cutting Regions," Annals of the CIRP, Vol. 47/1, pp. 335~338, 1988.
4. Wager, J. G. and Gu, D. Y., "Influence of Up-Grinding and Down-Grinding on the Contact Zone," Annals of the CIRP, Vol. 40/1, pp. 323~326, 1991.
5. Saini, D. P., "Wheel Hardness and Local Elastic Deflection in Grinding," Int. J. Mach. Tools Manufact., Vol. 30, No. 4, pp. 637~649, 1989.
6. Reshetov, D. N. and Portman, V. T., Accuracy of Machine Tools, ASME PRESS, pp. 273~275, 1988.