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SASAKI, Tokio; OKAMURA, Kenjiro

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By

Tokio SASAKI and Kenjiro OKAMURA

Department of Mechanical Engineering

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Summary

For the purpose of improving cutting performance of fine-grain abrasive stones, the authors investigated about numerous fine-grain abrasive stones of various bond hardness, bond combining ratio, porosity and grain combining ratio, using a special testing apparatus with which stone wear, stock removal and cutting resistance could be measured, and obtained the following results.

The results of the model performance test obtained with the testing apparatus designed by the authors coincide well with the results of practical superfinishing. The porosity is the most decisive factor on cutting performance among the constitutional factors of a fine-grain abrasive stone. In order to get a good cutting performance, it is necessary to use stones which maintain higher bond hardness with smaller quantity of bond and have larger porosity.

1. Introduction

Formerly the fine-grain abrasive stones were used mainly in the polishing operation which involved small amount of stock removal; however recently, even in such precision machining processes as honing and superfinishing, it is required to take more amount of stock removal to increase the machining efficiency. Thus the cutting performance of fine-grain abrasive stone becomes of more importantance.

Notwithstanding the fact that the characteristic of abrasive stone depends on the various constitutional factors such as abrasive grain, grain size, bond, bond hardness, bond combining ratio, porosity, grain combining ratio, etc., only the bond hardness was considered in the past as an important criterion in determining the cutting performance of abrasive stones. However, the abrasive stones of the same bond hardness often reveal different cutting performances.

In order to investigate the cutting performance of abrasive stone in view of the various factors including bond hardness, bond combining ratio, porosity and grain combining ratio, a special testing apparatus was designed with which stone wear, stock removal and cutting resistance could be measured; and a considerable number of different abrasive stones were tested with this testing apparatus. Comparing the test results obtained by the testing apparatus mentioned above with the practical operation of superfinish, the relations between various constitutional factors and cutting performance were clarified.

2. Experimental equipment and abrasive stone

Experimental equipment:

A drawing of the complete fine-grain abrasive stone testing machine is shown in Fig. 1. The workpiece ① is attached to the bottom end of main spindle ② and it is rotated at a constant speed by the main spindle driven by an electric motor through belt pulley ③ and coupling ④. The abrasive stone ⑤ is fixed on table ⑥ which can be rotated about an axis with minimum friction. As the moment acting on the table due to cutting resistance is balanced by the tension of spring balance ⑦ through thread ⑧, the table ⑥ stays still. The reading on spring balance, therefore, is the measurement of the cutting force between the workpiece and abrasive stone. The contact pressure between the workpiece and the abrasive stone is given by the weight of main spindle ② and disc ⑨ attached to ②. The stock removal and stone wear can be measured by dial gage ⑩. ⑪ is a cam used to lift main spindle and detach the workpiece from the surface of the abrasive stone.

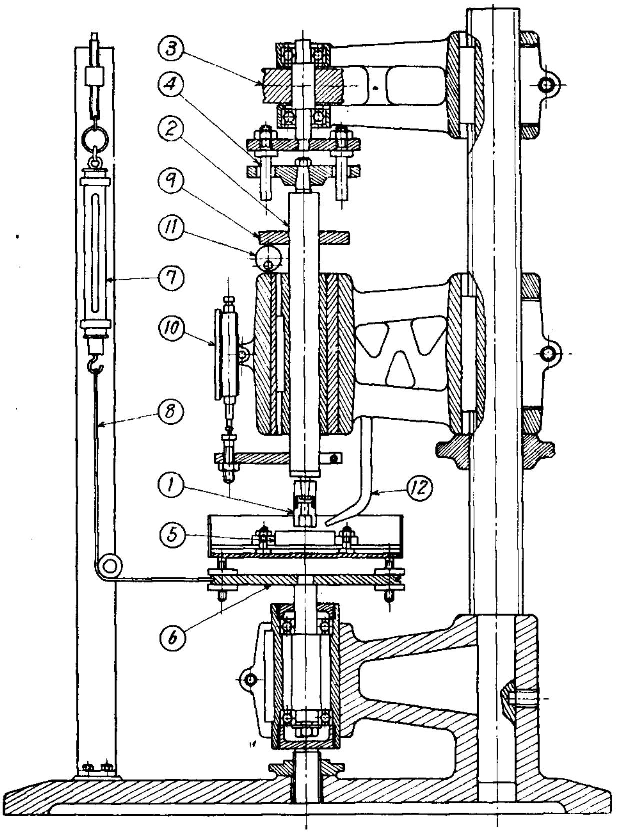

Fig. 1.

The cutting fluid is poured on the contact surface of the workpiece and the stone from pipe ⑫.

Fig. 2 shows the shape and size of the workpiece. The workpiece has eight radial grooves of 2 mm width for the purpose of eliminating the chips and falling off of abrasive grain and bond by pouring in the cutting fluid. The chemical composition of the workpiece made of steel is shown in Table 1.

Table 1.

Chemical composition %			
C	Si	Mn	Fe
0.43	0.44	0.95	98.18

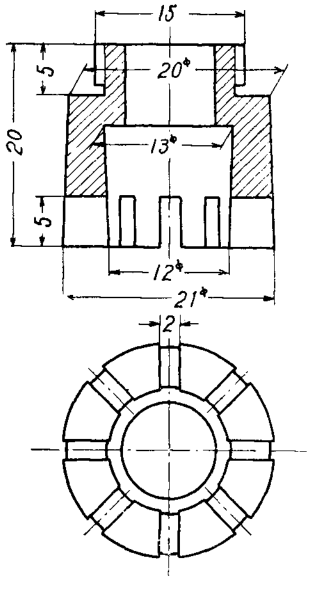

Fig. 2.

Table 2.

	B %	R_H	P %	ρ	ρ_{gb}	ρ_b	G %	a
I	39	92	40.6	1.95	3.28	2.33	35.8	1.137
	36	87	40.9	1.96	3.31	2.33	37.1	1.121
	33	80	42.7	1.92	3.34	2.35	37.1	1.121
	30	74	43.6	1.91	3.38	2.34	37.9	1.113
	27	77	43.0	1.93	3.40	2.29	37.6	1.116
	24	67	45.2	1.90	3.46	2.34	39.6	1.098
	21	63	44.4	1.95	3.51	2.38	41.8	1.078
	18	50	46.8	1.87	3.53	2.31	40.6	1.089
	15	43	47.9	1.86	3.57	2.30	41.1	1.084
	12	38	48.4	1.87	3.62	2.32	42.4	1.074
II	16	81	42.5	2.04	3.54	2.25	44.7	1.052
		86	41.9	2.06	3.54	2.25	45.3	1.049
		83	43.1	2.04	3.55	2.28	45.6	1.048
		74	44.2	1.98	3.54	2.25	43.5	1.062
		71	44.3	1.97	3.54	2.25	42.9	1.068
		65	45.7	1.93	3.56	2.31	42.8	1.069
		58	46.6	1.90	3.56	2.31	42.2	1.073
		52	47.6	1.87	3.56	2.31	41.5	1.080
		49	47.6	1.85	3.54	2.25	40.6	1.089
		44	48.3	1.83	3.54	2.25	40.1	1.092
III	23	86	47.2	1.82	3.45	2.29	37.9	1.113
	22	83	47.3	1.83	3.48	2.33	38.2	1.110
	21	80	47.4	1.85	3.50	2.34	39.8	1.100
	19	78	47.7	1.83	3.51	2.30	39.4	1.103
	18	76	48.4	1.83	3.54	2.34	39.7	1.098
	14	69	48.6	1.83	3.58	2.32	41.1	1.083
	13	65	48.5	1.86	3.60	2.29	41.6	1.080
	11	56	48.7	1.85	3.61	2.27	42.3	1.072
	9	48	49.2	1.84	3.65	2.28	42.5	1.071

Abrasive stone:

The abrasive stones used in this experiment have the following designation:— abrasive grain: Aluminum oxide, grit: 600 mesh, bond: Vitrified. The bond hardness (R_H), bond combining ratio (B), porosity (P) and grain combining ratio (G) are tabulated in Table 2. And these stones are composed of three groups I, II and III.

Group I consists of stones of varied bond hardness obtained by changing the bond combining ratio. Group II has definite bond combining ratio and different porosity. Group III has the same variety of bond hardness as group I, but has less bond content and higher bond hardness.

3. Characteristics of the abrasive stone used for the test

To measure the bond hardness (R_H), H scale of Rockwell hardness tester (with ⅛″ ball and 60 kg load) is used.

The bond combining ratio (B) is defined to be the ratio of the weight of abrasive grain to that of the bond

$$B=\frac{\text{Weight of bond } W_B}{\text{Weight of grain } W_G}$$

The porosity (P) is defined by the formula

$$P=\frac{W_2-W_1}{W_2-W_3},$$

where W_1 is the weight of the stone when it is dry, W_2 the weight of the stone containing water, and W_3 is the weight of stone measured in the water.

The specific weight (ρ) of the stone is defined by the formula

$$\rho=\frac{W_1}{W_2-W_3}.$$

The average specific weight (ρ_{gb}) of the abrasive grain and bond is defined by the formula

$$\rho_{gb}=\frac{W_1}{W_1-W_3}.$$

The specific weight of bond (ρ_b) may be computed by the formula

$$\rho_b=\frac{\rho_g\rho_{gb}B}{\rho_g(B+1)-\rho_{gb}},$$

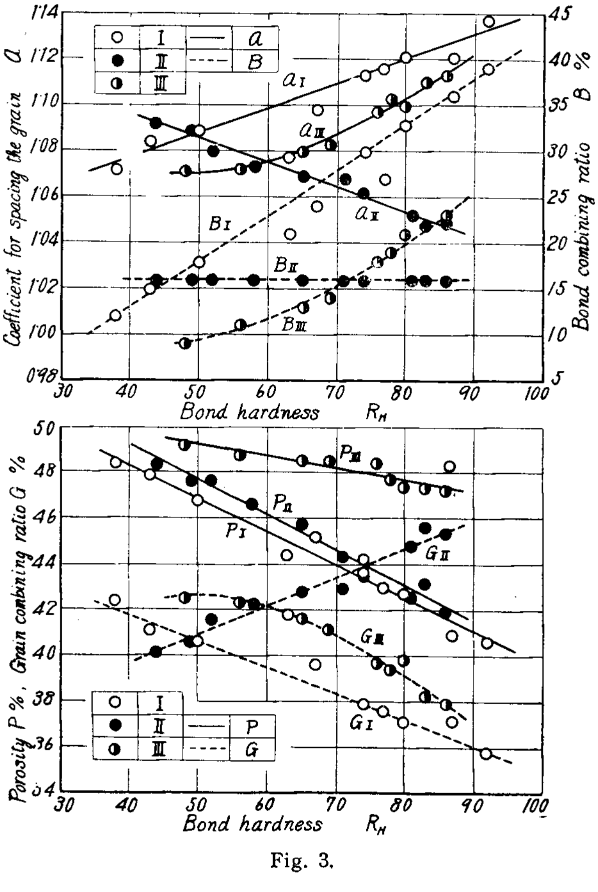

Fig. 3.

where ρ_g is the specific weight of the abrasive grain.

The bond combining ratio (G) is given by the following formula:

$$G=\frac{\text{Total volume of abrasive grains } V_G}{\text{Volume of stone } V}=\frac{1}{\rho_g-\rho_b}\{\rho-\rho_b(1+P)\}\,.$$

The coefficient for spacing the abrasive grain (a) is defined by the formula

$$a=\frac{\text{Space between grains } x}{\text{Average diameter of grain } d}=\sqrt[3]{\frac{\pi\rho_g}{6\rho}(1+B)}\,.$$

Fig. 3~Fig. 5 show graphically the relations between various factors in Table 2. As shown in Fig. 3, the groups I, II and III of abrasive stones have the same tendency about the porosity, although the group III has a greater value of porosity than the group I or II. In the relation of bond combining ratio, grain combining ratio and coefficient for spacing the abrasive grain to bond hardness, the groups I and III have the inverse tendency to the group II and the same facts are seen in Fig. 4 and Fig. 5.

Namely, the stones of the groups I, II and III have the different characteristics

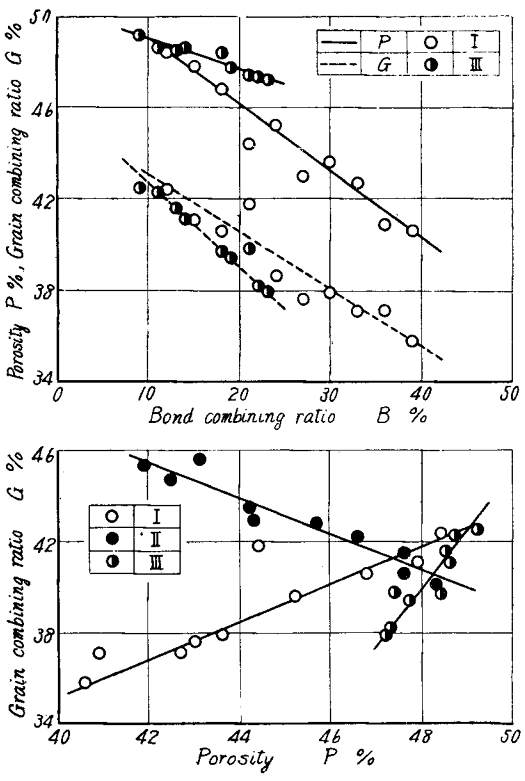

Fig. 4.

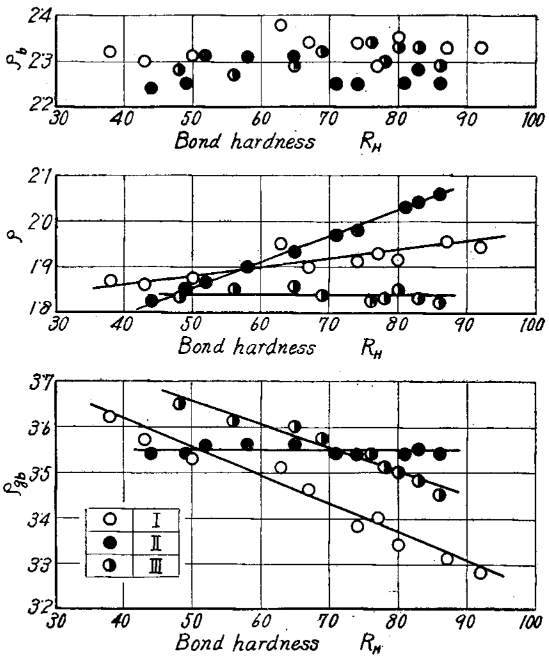

Fig. 5.

in the constitutional factors of stone. Accordingly, it is possible to find which constitutional factor has the most influence on the cutting performance by conducting this experiment.

4. Comparison between the cutting performance test and the superfinishing experiment

As the form of workpiece and the motion of abrasive stone in the testing apparatus shown in Fig. 1 are considerably different from the practical operation of superfinish, the results obtained with this testing apparatus are compared with the results obtained in practical operation of superfinish in order to confirm the utility of this experimental equipment.

Conditions of the cutting performance test:

The cutting speed, the contact pressure between the workpiece and stone, the cutting fluid and the cutting time are taken as the working conditions influencing the cutting performance test which the authors call the model performance test.

The cutting speed, i. e. the rotating speed of the workpiece, was set at 45 m/min. The contact pressure was set at 2.3 kg/cm^2, because 2.3 kg/cm^2 was the lowest contact pressure to allow an accurate measurement of the stone wear S, stock removal W and cutting resistance F, as the experiment with the stone of $R_H = 54$ is shown in Fig. 6. The cutting fluid was the mixture of kerosene (80%) and machine oil (20%), and the cutting time of 2 minutes was taken.

Conditions of the superfinishing experiment:

The mean cutting speed, the maximum cutting direction angle, the stone pressure, the cutting fluid and the superfinishing time are taken as the working conditions

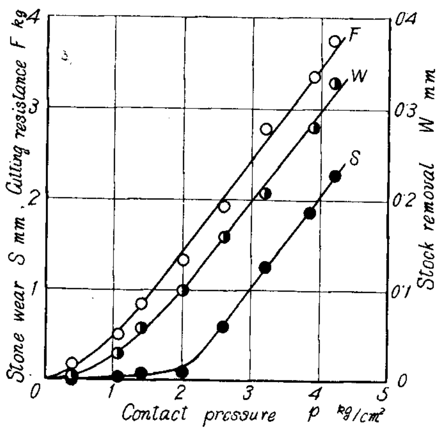

Fig. 6.

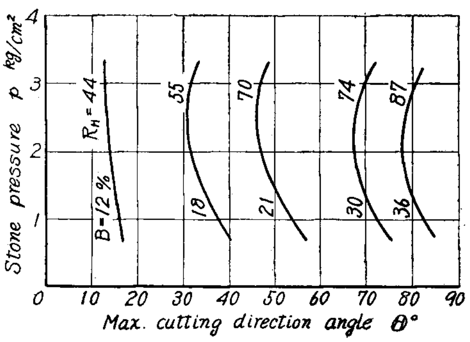

Fig. 7.

influencing the cutting performance.* Consequently it is necessary to select the most suitable working condition for every abrasive stone in order to get the correct comparison of superfinishing performance.

As reported already,* the best cutting performance of superfinish is obtained on the critical curve of cutting. Fig. 7 shows the critical curves of some abrasive stones of different bond hardness and bond combining ratio used in this experiment. After determining the stone pressure, the maximum cutting direction angle (Θ), which gives the critical point of cutting, can be determined by Fig. 7.

$$\Theta = \tan^{-1}\frac{v_s}{v_w} = \tan^{-1}\frac{af}{DN}$$

Where v_s is the maximum speed of stone, v_w the surface speed of workpiece, a the amplitude of oscillation, f the frequency of oscillation, D the diameter of workpiece, and N the rotation of workpiece.

The mean cutting speed $\bar{v}$ is given by the following formula:

$$\bar{v} = 2\{(DN)^2+(af)^2\}^{\frac{1}{2}}\int_0^{\frac{\pi}{2}}(1-\sin^2\Theta\sin^2\varphi)^{\frac{1}{2}}\,d\varphi\ ,$$

where φ is the angle of rotation of the eccentric axis.

In this experiment, a is 3 mm, D is 32 mm, and N, f are so chosen as to obtain a predetermined value of cutting direction angle (Θ) and the mean cutting speed of 20 m/min. In this case frequency f may be adjusted to take any value but the work speed can be changed only stepwise due to the mechanism of the machine tool, consequently the value of $\bar{v}$ can not be made exactly 20 m/min. The stone pressure and the kind of cutting fluid are taken to be the same as the model performance test described before, and the cutting time is chosen to allow the cutting length of 30 m.

Experimental results:

Fig. 8 shows the relation between stock removal and bond combining ratio and Fig. 9 shows the relation between stone wear and bond combining ratio under the machining conditions described above.

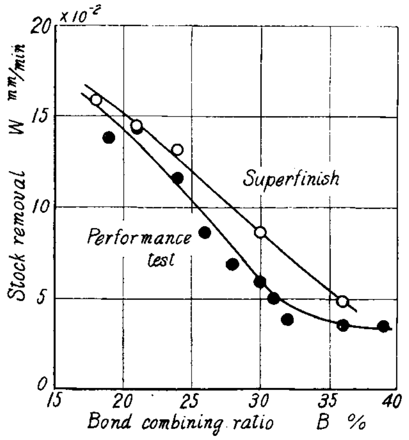

Fig. 8.

In Fig. 8, as the stock removal of superfinish,

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* T. SASAKI & K. OKAMURA: Fundamental Research of the Superfinish. Memoirs of the Faculty of Engineering Kyoto University, Vol. 16, No. 3, July, 1954. p. 157.

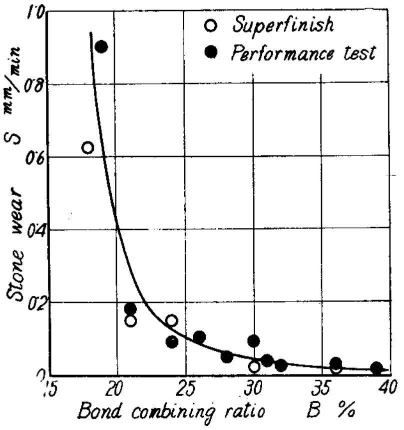

Fig. 9.

Table 3.

	R_H	F kg	W μ/min	S μ/min	Z mm
I	92	0.42	35	5	0.15
	87	0.46	36	10	0.28
	80	1.44	38	20	0.53
	74	1.60	53	30	0.57
	77	1.65	80	45	0.57
	67	1.84	105	60	0.58
	63	1.86	123	170	1.39
	50	1.91	143	520	3.64
	43	1.83	158	1125	7.32
	38	1.85	163	3275	20.30
II	81	1.47	86	35	0.36
	86	1.43	92	30	0.33
	83	1.44	91	30	0.33
	74	1.58	112	50	0.45
	71	1.62	115	75	0.65
	65	1.55	113	105	0.92
	58	1.59	119	185	1.56
	52	1.67	124	365	2.96
	49	1.67	131	275	2.12
	44	1.67	139	380	2.74
III	86	1.83	132	120	0.91
	83	1.86	154	155	0.98
	80	1.87	152	195	1.29
	78	1.86	161	185	1.15
	76	1.88	163	240	1.48
	69	1.97	169	530	3.14
	65	1.95	166	840	5.07
	56	1.95	173	940	5.43
	48	1.86	164	1820	11.21

the equivalent value is adopted with which the total length of contact between a point on the workpiece and the abrasive stone becomes the same as in the model performance test. Also in Fig. 9, as the stone wear of superfinish, the equivalent value is adopted with which the total length of contact between a point on the abrasive stone and the workpiece becomes the same as in the model performance test.

In Fig. 8 the same tendencies appear in the relations between the stock removal and bond combining ratio for both the model performance test and the practical superfinish test, and the curves of stone wear for the two tests entirely coincide as shown in Fig. 9. Accordingly, it is recognized that the cutting performance of the superfinishing stone can be found by the model performance test described above.

5. Relation between the constitutional factors of abrasive stone and the cutting performance

The experimental results of model performance test are shown in Table 3 for the groups I, II and III of Table 2. The symbols F, W, S and Z denote respectively the cutting resistance, the stock removal per unit time, the stone wear per unit time and the stone wear required for cutting 1 mm of workpiece, or the stone wear ratio.

Cutting resistance:

As shown in Fig. 10, the cutting resistance of almost all abrasive stones used in the test lies within the range of 1.5~2.0 kg. In other words, the cutting resistance is not very much influenced by the constitutional factors of the abrasive stone. As the abrasive stone does not cut the workpiece when the cutting resistance is smaller than 1 kg, the resistance in this case should be considered as the frictional resistance. Stones of small cutting resistance have large bond combining ratio and small grain combining ratio.

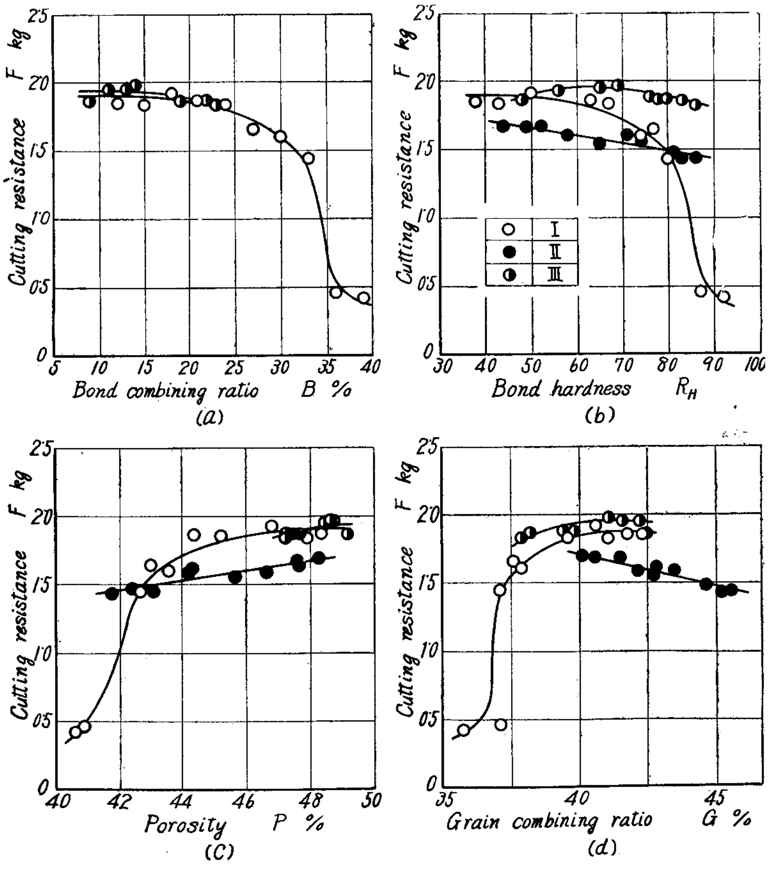

Fig. 10.

Stock removal:

Fig. 11 shows the experimental results on stock removal. The stock removal rapidly decreases with the increase of bond combining ratio as shown in Fig. 11 (a). Three curves of stock removal against bond hardness R_H do not coincide well as shown in Fig. 11 (b). Thus, it is concluded that the bond hardness is not a decisive factor for the cutting performance. In Fig. 11 (c) the stock removals increase linearly with the increase of porosity, and three curves coincide comparatively well. Therefore, it may be said that the influence of porosity on the stock removal is considerable and that the porosity is a decisive factor on the cutting performance. As shown in Fig. 11 (d), it is recognized that the grain combining ratio is not a decisive factor on the cutting performance.

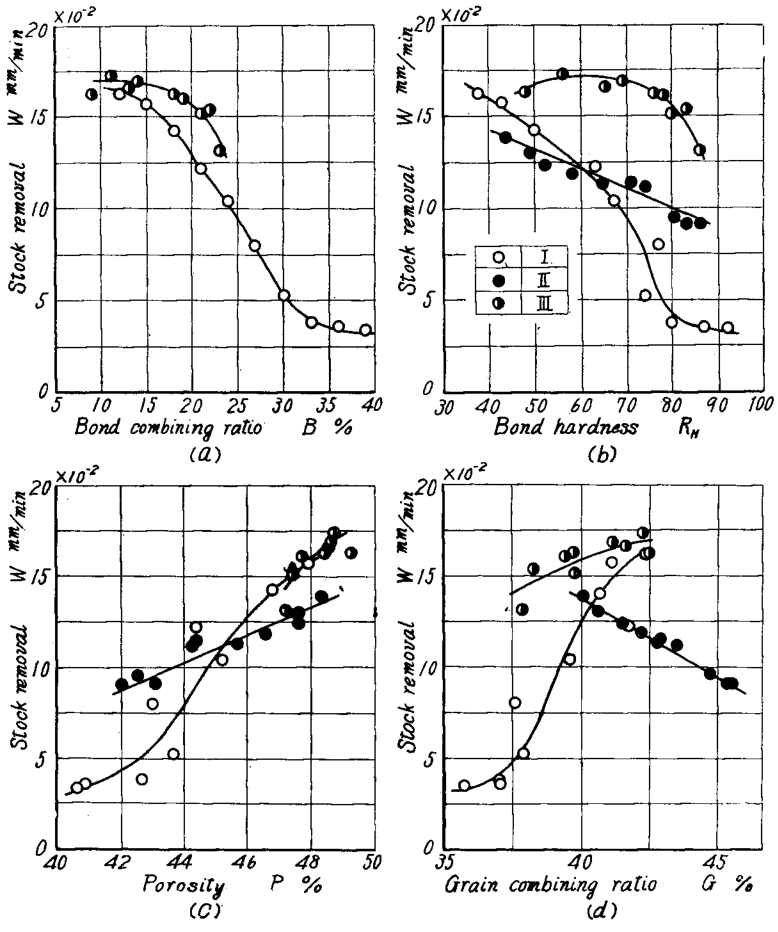

Fig. 11.

Stone wear:

Fig. 12 shows the experimental results on stone wear. As seen in Fig. 12 (a), (b), (c) and (d), the curves for the groups I, II and III do not coincide well. Therefore, it is concluded that none of the factors B, R_H, P and G alone has a decisive influence on the stone wear and that the resultant effect of these factors, with an exception of G, decide the stone wear. It is considered, therefore, that larger bond combining ratio and bond hardness and smaller porosity yield smaller stone wear.

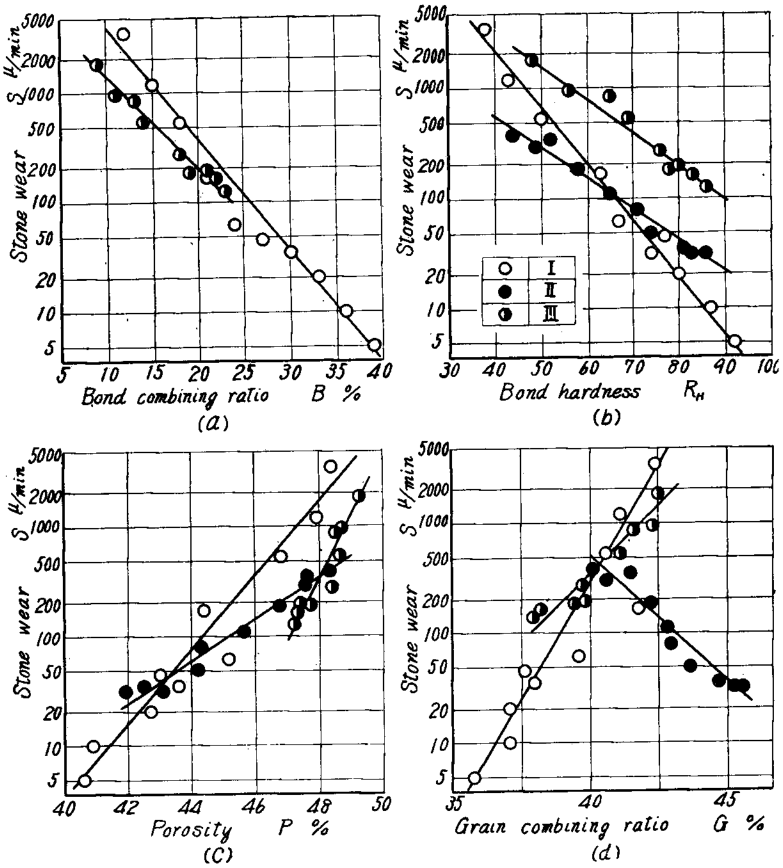

Fig. 12.

Stone wear ratio Z:

A smaller value of stone wear ratio Z means a larger stock removal per unit stone wear, or in other words, better state of stone cutting. As shown in Fig. 13 the relations between the stone wear ratio Z and the factors B, R_H, P and G resemble the relations shown in Fig. 12, and consequently the effect of constitutional factors of stone to Z is similar to that of the stone wear discussed above.

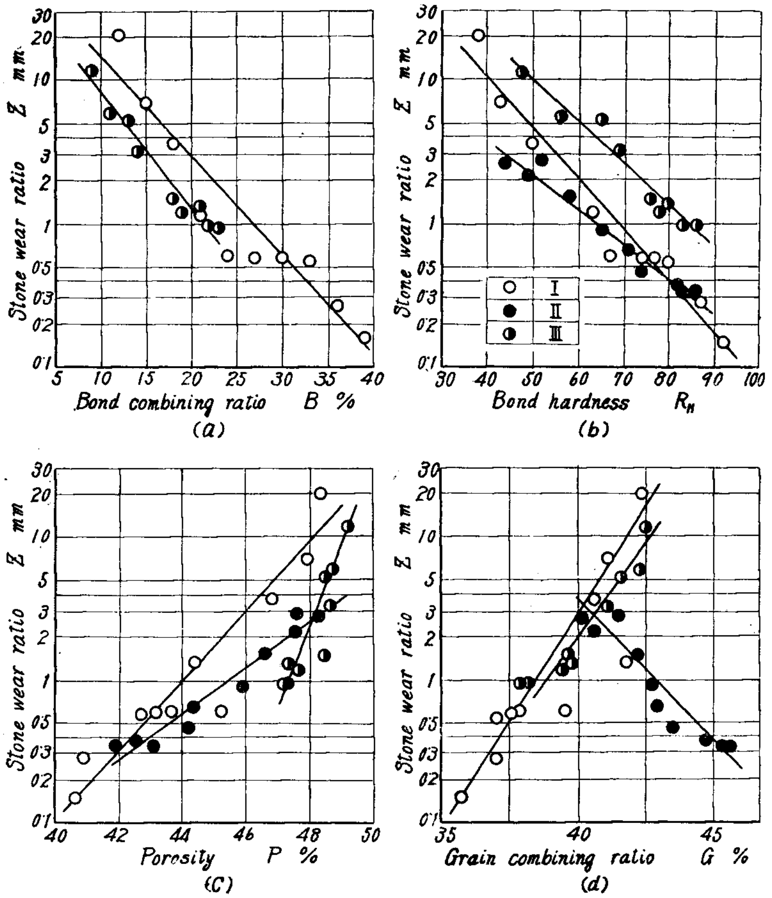

Fig. 13.

6. Discussions on the experimental results of the model performance test

In order to improve the cutting performance of fine-grain abrasive stone, it is necessary to select the constitutional factors of stone so as to increase the stock removal *W* and decrease the stone wear ratio *Z*. According to our experimental results, larger stock removal may be obtained with the stone of smaller bond combining ratio and larger porosity; also, smaller stone wear ratio *Z* may be obtained with the stone of larger bond combining ratio, larger bond hardness and smaller porosity.

As described above, the conditions of selection of stones for the purpose of obtaining larger stock removal are contrary to those for obtaining the smaller stone wear ratio. Therefore, the constitutional factors of abrasive stone should be chosen considering the relative importance of shortening the working time and saving the stone wear. However, as shown in Fig. 11 and Fig. 13, the stones of group III always give a superior cutting performance than the stones of the groups I and II.

Thus, in order to improve the cutting performance of fine-grain abrasive stone, it is necessary to use a stone of higher bond hardness with smaller bond combining ratio which has a larger grain combining ratio and a larger porosity.

7. Conclusions

The above study leads to the following conclusions:

(1) The results of model performance test obtained with the testing apparatus which is newly designed by the authors to enable the testing of the cutting performance of fine-grain abrasive stone, coincide well with the results of practical superfinishing.

(2) The cutting resistance is not much influenced by the constitutional factors of fine-grain abrasive stone.

(3) The porosity is the most influential factor on the cutting performance among the constitutional factors of abrasive stone.
The grain combining ratio is not a decisive factor on the cutting performance.

(4) In order to get a good cutting performance, it is necessary to use the abrasive stone of higher bond hardness with smaller bond combining ratio (less than 20%) and larger porosity (greater than 45%).