Title	Consideration of centerless grinding characteristics through harmonic analysis of out-of-roundness curves
Sub Title	
Author	米津, 栄(Yonetsu, Sakae)
Publisher	慶応義塾大学藤原記念工学部
Publication year	1959
Jtitle	Proceedings of the Fujihara Memorial Faculty of Engineering Keio University Vol.12, No.47 (1959.) ,p.184(8)- 202(26)
JaLC DOI	
Abstract	A centerless grinder will often produce work of a uniformly constant, but is far from round, so called "Gleichdicke". There are many troubles, such as concentrated stress in an interference fit and seizure in a clearance fit, but it is seemed that there is no general research as to rounding up action in centerless grinding. Then, in this paper, the author inspected experimentally on the relations of the out-of-roundness curve for cylindrical work before and after centerless grinding by means of harmonic analysis, that is, on amplitude and phase of the out-of-roundness.
Notes	The twentieth anniversary memorial volume
Genre	Departmental Bulletin Paper
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO50001004-00120047-0008

Consideration of Centerless Grinding Characteristics Through Harmonic Analysis of Out-of-Roundness Curves

Sakae YONETSU*

Abstract

A centerless grinder will often produce work of a uniformly constant, but is far from round, so called "Gleichdicke". There are many troubles, such as concentrated stress in an interference fit and seizure in a clearance fit, but it is seemed that there is no general research as to rounding up action in centerless grinding. Then, in this paper, the author inspected experimentally on the relations of the out-of-roundness curve for cylindrical work before and after centerless grinding by means of harmonic analysis, that is, on amplitude and phase of the out-of-roundness.

I. Introduction

It has long been known that centerless grinding has the disadvantage of often producing cylindrical products which are uniform in diameter but far from round, i, e., of a shape called "Gleichdicke" or other characteristec shapes in centerless grinding.(1)(2)(3) Use of products of such shapes causes such problems as concentrated stress in an interference fit and seizure in a clearance fit.(4)(5) It appears, nevertheless, that there have been no theoretical studies providing general analysis of reasons for the appearance of such shapes. Past studies on the shape of the cross section of the centerless grinding work, lacking proper analytical consideration of the measuring method and measuring results, hardly make possible an overall examination of individual higher harmonic waves in the out-of-roundness curve, nor indicate clearly the relationship between the out-of-roundness curves of the work before and after it is subjected to centerless grinding.(6) Through harmonic analysis of the out-of-roundness curves of such work, this writer examined the characteristics of centerless grinding on the basis of his experiment results.

II. Experimenal method & conditions

The machine used for the experiments is NF16-type centerless grinder (Fig. 1),

* Doctor of Engineering, Keio Gijuku Univ. professor.

with the bearing adjusted with particular care to minimize vibrations. The grinding wheel was 400 mm × 150 mm–WA–60–M–V and the regulating wheel 230 mm × 150 mm–A–120–P–R. The top angle of the blade was $\phi=60°$ as a rule, and the blade was made of quenched steel ($R_c=57$), finished by lapping after grinding.

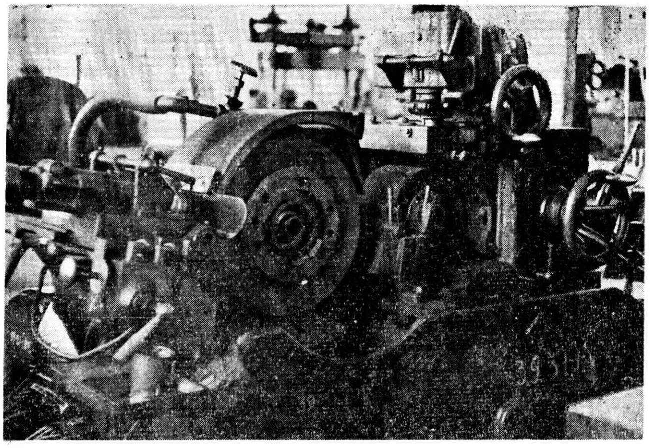


Fig. 1.

The work specimens were of hard steel (0.97% C), quenched and tempered ($R_c=68$), and 30 mmϕ × 100 mm in size.

Of the various methods of centerless grinding, the "in-feed method", considered the most basic, was adopted. The cut-in time was within 0.5 sec, and the total of this time and the duration of grinding was 25 seconds as a rule. Fig. 2 shows the performance cycle nf in-feed grinding.

Of the various work conditions, attention was given not merely to grinding conditions but also to work supporting conditions, in which centerless grinding is considerably different from ordinary center grinding. Worksupporting conditions are generally expressed in terms of α and β as shown in Fig. 3. However, as the diameters of the grinding wheel, the regulating wheel and the work were constant in the present cases, they were indicated by the work supporting height H and the top angle of the blade ϕ.

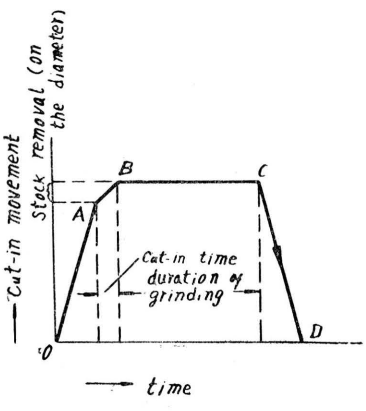


Fig. 2.

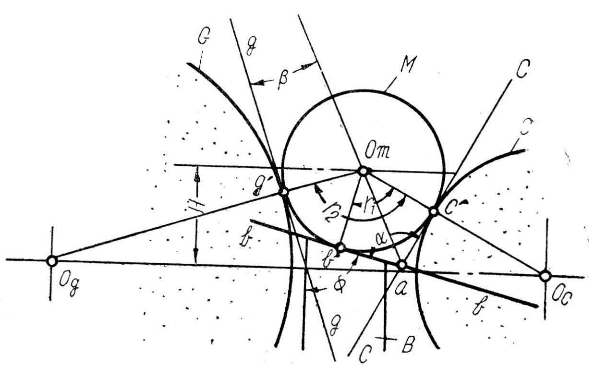


Fig. 3.

Some of the experiments were made under the following constant conditions:

circumferential velocity of the grinding wheel $V_g = 33.5$ m/s, circumferential velocity of the regulating wheel $V_c=28.9$ m/min., depth of cut in terms of the work's diameter$=20\mu$, and $\phi=60°$, with H alone varied from-3.5 to 0, 3.5, 7.5 and 15mm; in other experiments, H was kept constant at 7.5mm, with ϕ alone variously set at four stages, 40°, 60°, 75°; and 90°; in still other experiments conducted under constant work supporting conditions ($\phi=60°$ or 70° with $H=7.5$mm), the stock removal in terms of the work diameter reduction alone was varied among three stages, 10, 20 and 40μ, and then with the circumferential velocity of the regulating wheel alone varied among 12.3, 21, 28.9 39.8 and 56.4 mm/min.

In some of the experiments, emulsified oil, a Standard Vacuum Oil Co. Product, was used as coolant, but in the majority of the experiments the material was the Showa Oil-made Fuji-brand coolant (emulsified oil). One part of this was mixed with 10 parts of water, and the mixture was poured over the work from above at the rate of 240 l/min.

The specimens were all measured as to their out-of-roundness before and after their grinding by the so-called temporary center method, and the results were subjected to harmonic analysis. Namely, as shown in Fig. 4, each work specimen was held by the two center holes. Its periphery was divided into 24 equal parts, in each of which the radius variation was measured with a micro-indicator, and the eccentricity error of the work's center of rotation due to the center supporting was eliminated by calculation.

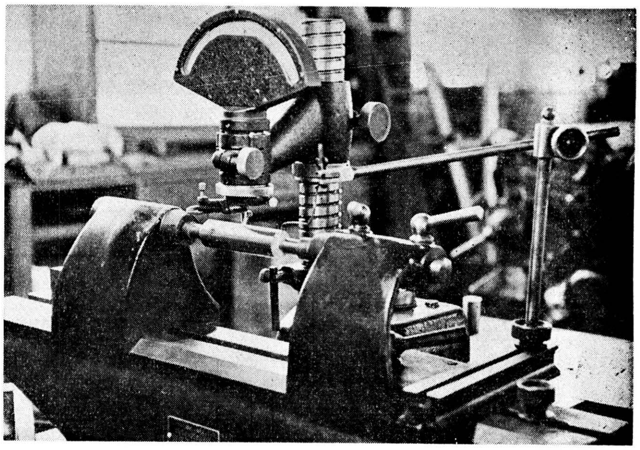


Fig. 4

Also, to study the relationship between the pre-grinding and post-grinding values of the various elements involved in the harmonic analysis of the out-of-roundness curves, the end surfaces of each work specimen were marked with diamond cuts radially dividing the circumference of each surface into 24 equal parts. These cuts were taken as marks of a system of coordinates fixed on the surface.

III. Elements determining out-of-roundness curve

To begin with, let us see the method employed by this writer to analyze the results of his experiments.

Generally, the profile curve of the cross section of a cylindrical object is expressed by its polar tangential coordinates in the form of a Fourier series, as follows:

$$r(\theta)=a_0+a_1\cos\theta+a_2\cos 2\theta+a_3\cos 3\theta+\cdots\cdots\cdots \\ +b_1\sin\theta+b_2\sin 2\theta+b_3\sin 3\theta+\cdots\cdots\cdots \tag{1}$$

or

$$r(\theta)=a_0\sum_{i=1}^{\infty}C_i\cos(i\theta+\varphi_i) \tag{2}$$

with

$$\left.\begin{aligned} C_i&=\sqrt{a_i^2+b_i^2} \\ \varphi_i&=-\tan^{-1}(b_i/a_i) \end{aligned}\right\} \tag{3}$$

where a_0 is the average radius; C_1, deviation of the origin from the average circle center; φ_1, angular deviation of the average circle center from the original line. These have nothing to do with the out-of roundness itself, whereas the following do have something to do with the out-of-roundness:

$$u(\theta)=\sum_{i=2}^{\infty}C_i\cos(i\theta+\varphi_i) \tag{4}$$

and

$$u'(\theta)=\sum_{i=2}^{\infty}C_i'\cos(i\theta+\varphi_i') \tag{5}$$

The curves determined by these are here defined as the pre-grinding and post-grinding out-of-roundness curves, respectively. In each case, harmonic analysis of the outline curve of the cross section of the work will determine C_i, and φ_i (or C_i', and φ_i') from (3).

In this paper, the following terms in alternating current theories and acoustics are tentatively adopted for the convenience of examining as a whole the wave shape of the out-of-roundness curve.

(i) $C_i\cos(i\theta+\varphi_i)(i=2, 3, \cdots\cdots)$: Higher harmonic of the out-of-roundness curve, with i called the number of order for the higher harmonic,

(ii) $C_i(i=2, 3, \cdots\cdots)$: Amplitude of the higher harmonic,

(iii) $\varphi_i(i=2, 3, \cdots\cdots)$: Phase of the higher harmonic,

(iv) Illustration of the values of C_i expressed by horizontal parallel bars arranged at equal intervals in the order of $i = 2, 3, \cdots\cdots$: Out-of-roundness spectrum, with post-grinding quantities marked with (′) to be distinguished from their pre-grinding counterparts.

IV. C'_i - C_i curves and work supporting conditions

IV. 1 Expeimrent results

First, in order to see the relationship between the pre-grinding and post-grinding higher harmonic amplitudes, specimens with out-of-roundness within the range of 0.4—7 μ were used in a number of tests with the work supporting height —— the distance between the work center and the line between the centers of the wheels —— varying from −3.5 through 0, 3.5 and 7.5 to 15 mm. The relationship between C_i' and C_i for each i value is illustrated in Fig. 5, where it is seen that the cylindrical work specimens show much larger higher harmonic amplitudes for odd-munber values of i than for other i values, showing Gleichdicke or nearly Gleichdicke shapes. The Fig. 5 graphs are for higher harmonic amplitudes for odd-number values of i.

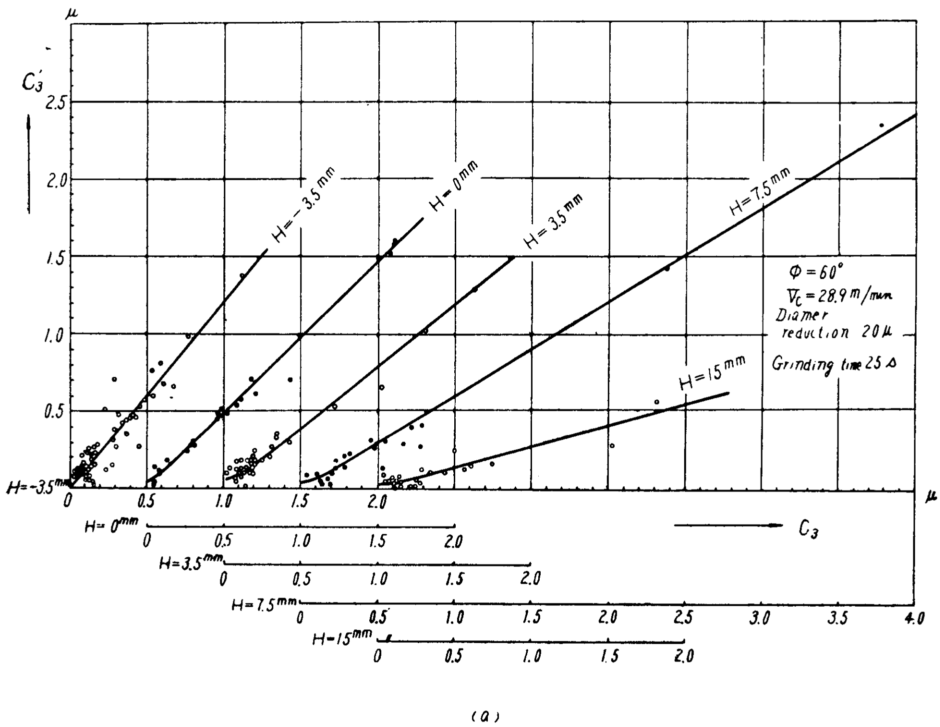
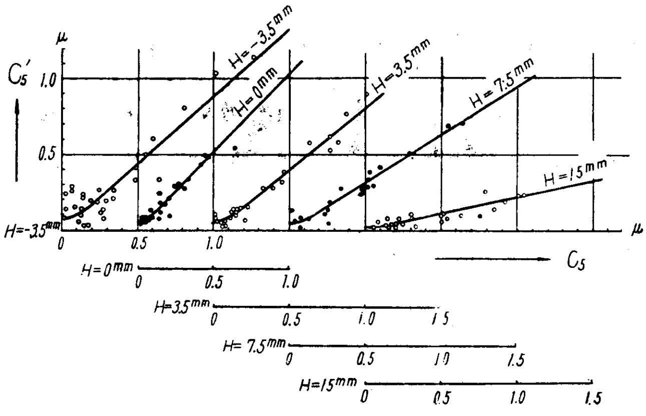
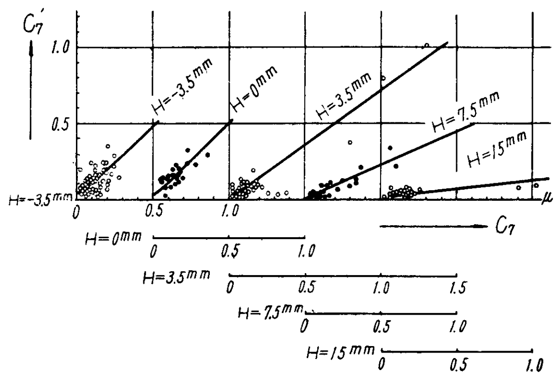


Fig. 5. (*a*)



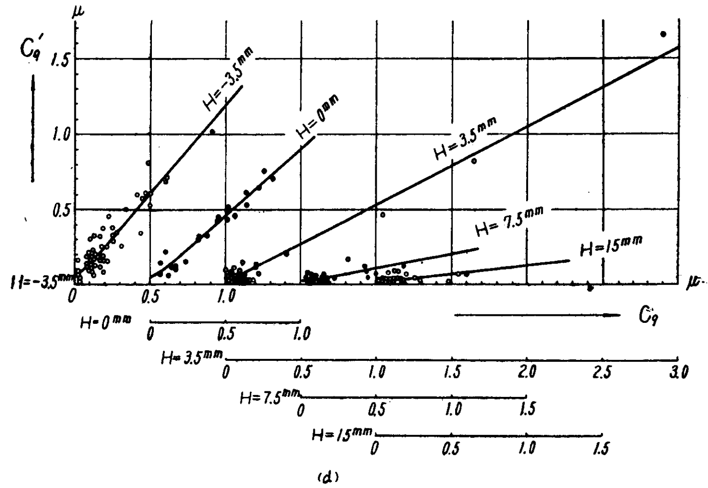
(b)

Fig. 5. (b)



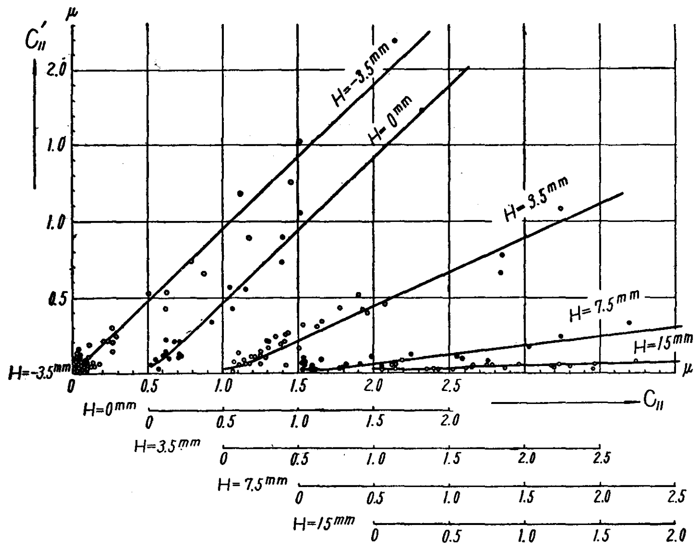
(c)

Fig. 5. (c)



(d)

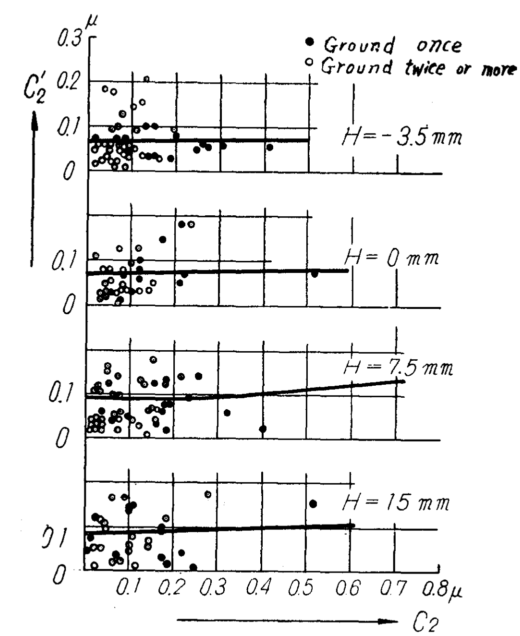
Fig. 5. (d)



(e)

Fig. 5. (*e*)

Next, instead of specimens of special shapes as mentioned above, a number of specimens prepared by center grinding with out-of-roundness within the range of 0.3—3.1 μ were subjected to centerless grinding, and the relationship between C_i' and C_i was figured out for each i value. The results are shown in Fig. 6 and 7. Fig. 6 (a)—(e) are for even-number values of i (i=2, 4, 6, 8, 10) and Fig. 7 (a)—(e) are for its odd-number values (i = 3, 5, 7, 9, 11). Each dot in the figures represents a specimen prepared by center grinding and then subjected to centerless grinding, whereas a white dot ° represents a specimen thus ground once and then subjected to repeated centerless grinding.



(a)

Fig. 6. (*a*)

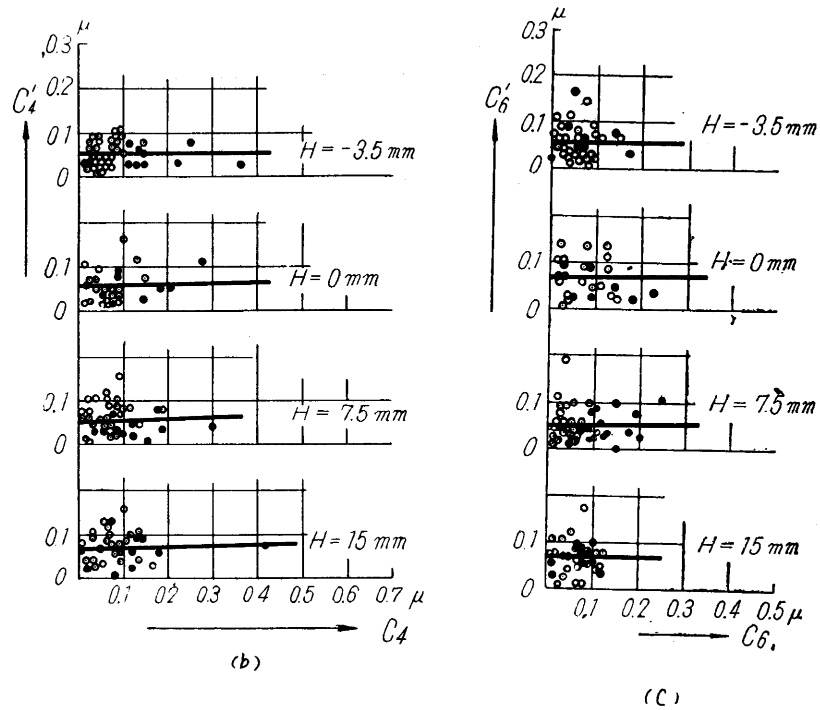


Fig. 6. (*b*), (*c*)

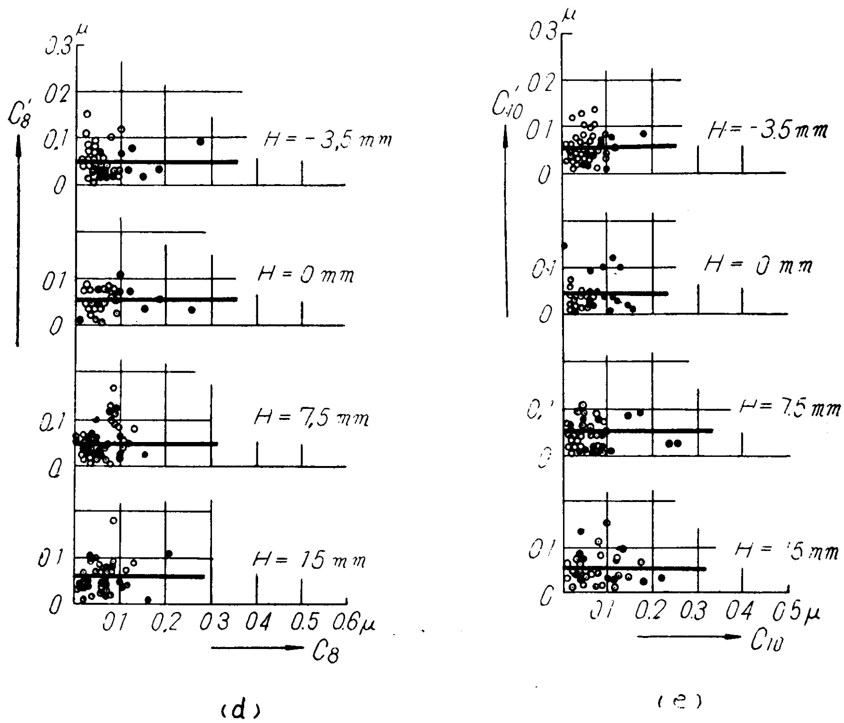
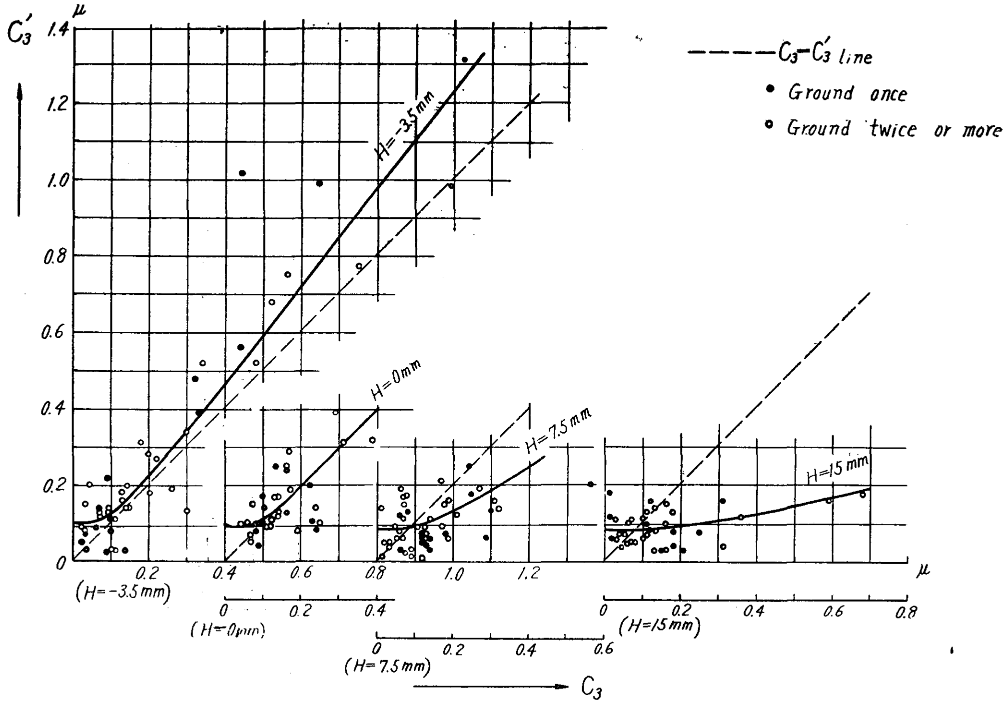
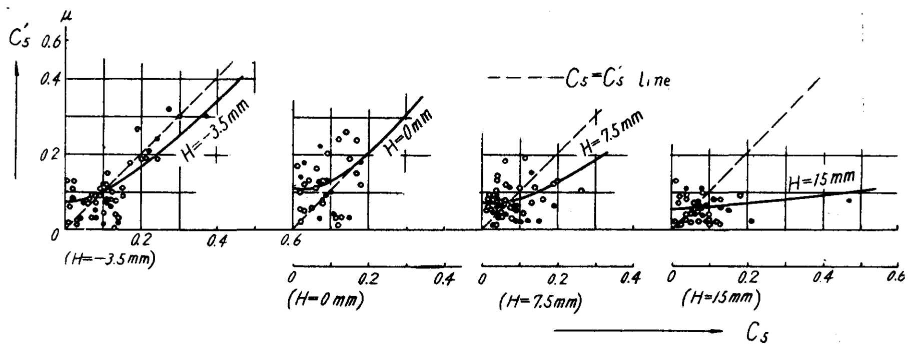


Fig. 6. (*d*), (*e*)



(a)

Fig. 7. (*a*)



(b)

Fig. 7. (*b*)

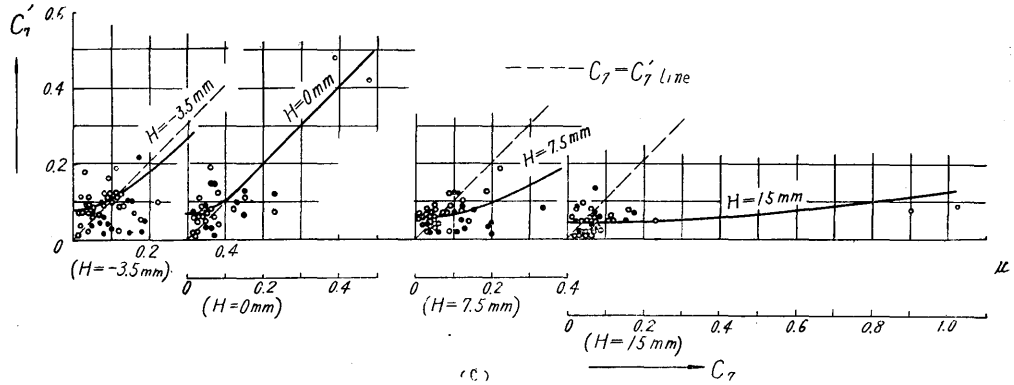
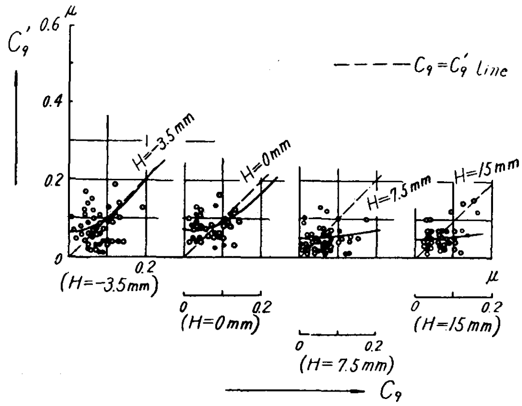
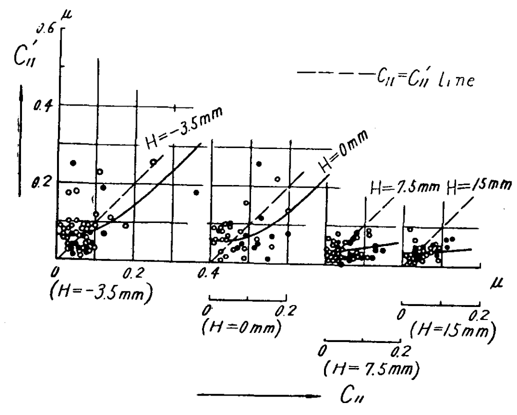


Fig. 7. (*c*)



(d)

Fig. 7. (*d*)



(e)

Fig. 7. (*e*)

In Fig. 5, 6 and 7, the dotted line from the origin represents $C_i'=C_i$, forming an angle of 45° with the C_i axis. It is drown as a means of seeing whether C_i' is larger or smaller than C_i in each case represented by a dot. This can be seen from whether the dot is above or below the line.

Looking over Fig. 5, 6 and 7, we find the following:

(i) Regardless of how many times a specimen is subjected to centerless grinding, its higher harmonic amplitudes vary independently for each number of order (Fig. 6, 7).

(ii) Between C_i' and C_i are relationships approximately represented by the solid-line curves. When $i=2n+1$ ($n=1, 2, 3, 4, 5$), C_i' depends largely on the magnitude of C_i, becoming smaller as C_i decreases; but as C_i increases, it may be considered that C_i' is approximately in a linear relationship with C_i along a straight line passing the origin.

(iii) When $i=2m$ ($m=1, 2, 3, 4, 5$), C_i' is generally independent of C_i.

(iv) When $i=2n+1$ ($n=1, 2, 3, 4, 5$), the $C_i'-C_i$ relationship varies considerably according to the work supporting height H.

IV. 2 Amplitude characterisitcs of higher harmonics vs work supporting height

In Fig. 5, 6 and 7, again, the relationship berween the pre- and post-grinding higher harmonic amplitudes is generally characterized by the following: the amplitude characterisitc may be expressed by the post-grinding amplitude for the pregrinding higher harmonic amplitude of 0, or by the ratio of the post-grinding amplitude to the pre-grinding amplitude when pre-grinding amplitude is very large. Here, for simplicity's sake, let us call the former C_{io} and the latter C_i, and determine them by means of empirical formulas.

(i) C_{io} vs. work supporting height.

As for the magnitude of C_{io}, in the first place, it is practically difficult to prepare specimens in which C_i is 0. Therefore from among the specimens used in the experiments mentioned in the last section, those with very small out-of-roundness were chosen and their C_{io} values were estimated by the exterpolation. When $i=2m$ ($m=1, 2, 3, 4, 5$), the $C_i'-C_i$ curve is considered to run roughly along a horizontal straight line as in Fig. 6. When $i=2n+1$ ($n=1, 2, 3, 4, 5$), the $C_i'-C_i$ curve is nonlinear while C_i is small, but when $C_i=$ is very small, or $C_i \leqq 0.1\mu$, it runs as shown in Fig. 8, and consequently may be represented approximately by a horizontal straight line. C_{io} values thus obtained by the exterpolation from $C_i'=C_{io}$ ($C_i \leqq 0.1\mu$) are shown against the work supporting height in Fig. 9.

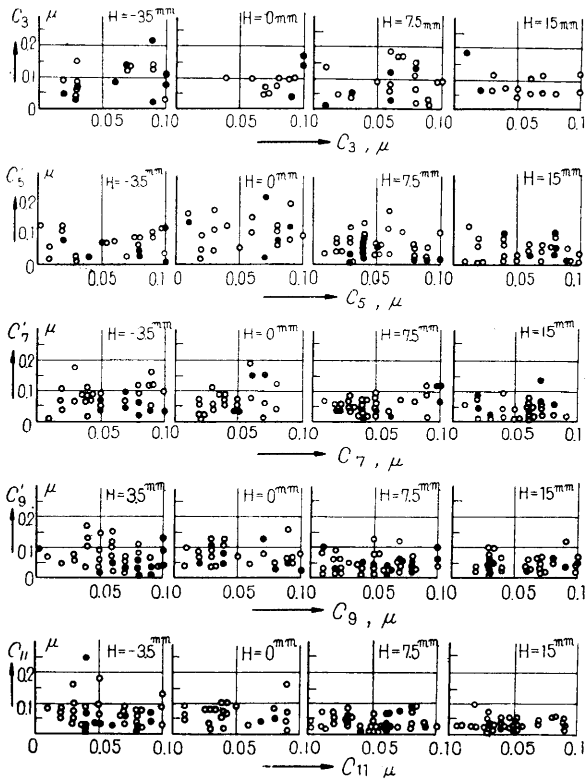


Fig. 8.

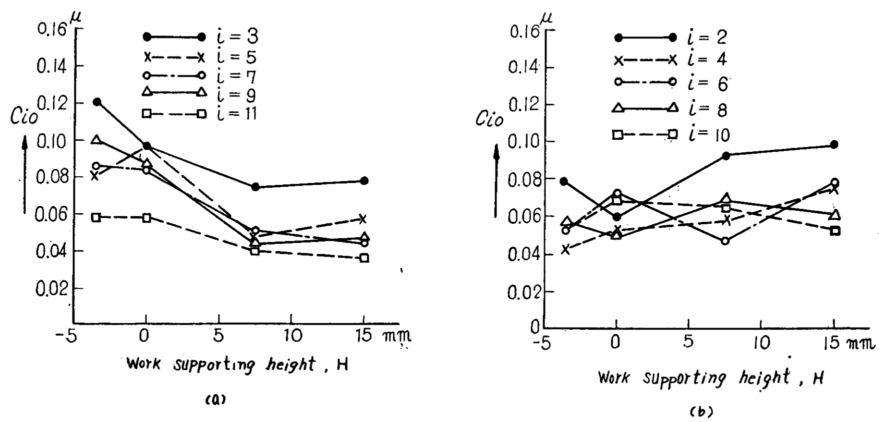


Fig. 9. (*a*), (*b*)

As is seen from the figures, the magnitude of C_{io} depends on the number of order i. Moreover, within the range of $H= -3.5 - 15$ mm, C_{io} depends on H when $i = 2n+i$ $(n=1, 2, 3, 4, 5)$, but C_{io} is not much influenced by H when $i=2m$

($m=1$, 2, 3, 4, 5), except when $i=2$. And since C_{io} is the post-grinding amplitude for the original C_i value of 0, it is seen that even a perfectly round specimen, when subjected to centerless grinding, is often finished with an out-of-roundness curve with larger amplitudes for odd numbers of order than for the others, and that with the work supporting height at 0 or in its neighborhood, it is liable to be finished in a "Gleichdicke" shape.

(ii) a_i vs. work supporting height:

From the experiment results in Fig. 5, a_i valves were figured out by means of the following:

$$C_i' = a_i C_i$$

and the results are shown against the work supporting height H in Fig. 10, from which it is seen that, when the work supporting height is within the range of $0-15$mm, a_i becomes smaller as the supporting height increases, and that, when the supporting height is -3.5mm or smaller than 0, a_i is smaller than when supporting height is 0, except when $i=3$, 9. Moreover, a_i generally depends on the number of order, but when the supporting height is 0, a_i roughly equals 1 irrespective of the number of order (only when it is an odd number).

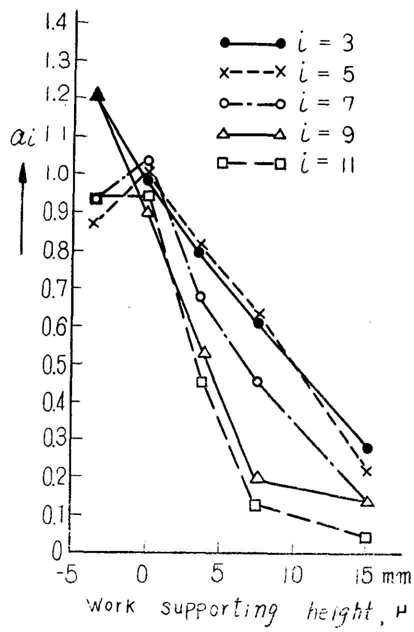
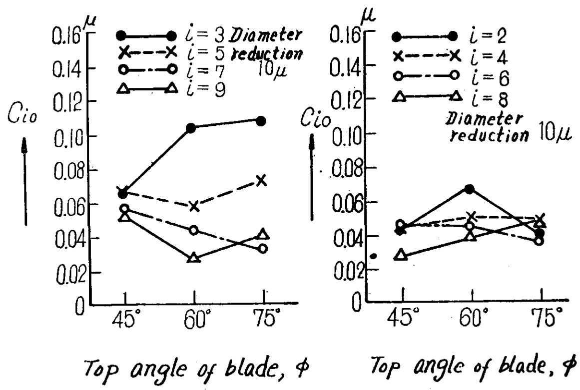


Fig. 10.

Consequently, a work specimen which is originally "Gleichdicke" in shape is not relieved of Gleichdicke errors after it is ground at the supporting height of 0, but when the supporting height is within the range of $0\sim15$ mm, the greater the supporting height is, the easier it is to remove the Gleichdicke and when the supporting height is -3.5mm, or smaller than 0, for numbers of order below 11, triangular and nonagonal shapes alone tend to have larger Gleichdicke errors than before the grinding.

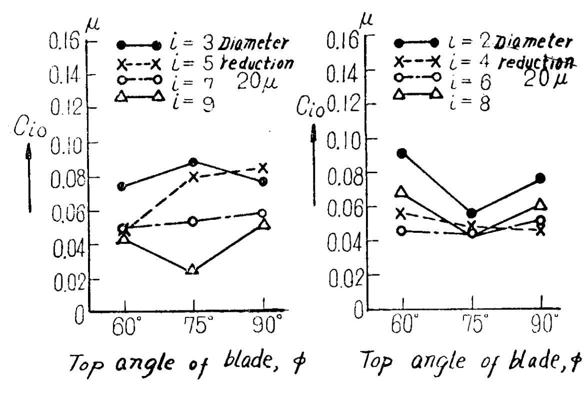
IV. 3 Top angle of the blade vs. amplitude characterisitics of higher harmonics

Next, with the work supporting height held constant, another work supporting condition, the top angle of the blade, was varied in a series of experiments to see what characteristics centerless grinding has as to C_{io} and a_i. The top angle ϕ of the blade was set at four stages 45°, 60°, 75° and 90°. When it is 45°, chattermarks in apt to be caused if the depth of cut in terms of the work diameter reduction is as much as to 20μ; therefore, in some experiments it was 10μ with ϕ set variously at 45°, 60° and 75°, whereas in others the depth of cut was 20μ with ϕ set variously at 60°, 75° and 90°. The rasults are illustrated in Fig. 11 and 12.



(a) (b)

Fig. 11. (a), (b)



(a) (b)

Fig. 12. (a), (b)

Similarly, a number of experiments were conducted with the supporting height $H=7.5\,\text{mm}$ and the top angle of the blade $\phi=90°$. The a_i values obtained in these experiments and the C_i values in the last section's experiments with $\phi=60°$ are shown for comparison in Table 1.

From Fig. 11 and 12 and Table 1, it is seen that neither C_{io} nor C_i is affected much by the top angle of the blade but that they vary slightly according to the number of order. From the above experiment results and the findings in the last section, it seems that C_{io} and a_i vary markedly accordings the work supporting height among the various work supporting conditions, but that they are not much affected by the top angle of the blade.

Table 1.

ϕ	60°	90°
a_3	1.20	0.97
a_5	0.88	0.95
a_7	0.93	0.96
a_9	1.20	0.98
a_{11}	0.94	0.99

IV. 4 Phase differencies of higher harmonics due to centerless grinding

In this section we will look into the phase of the higher harmonic wave, which, together with its amplitude, defines the out-of-roundness curve.

Each end of the work specimen, as was stated in chapter 2, bears radial cuts which divide its circumference into 24 equal parts. Therefore, the difference between the pre- and post-grindlng phases of the harmonic wave may be figured out in the light of these original lines fixed on the work. The harmonic phase φ_i (or φ'_i) can be obtained by means of eq. (3). As to its sign and angle determination, we will have the following agreement: As shown in Fig. 13 (a, b), the sign and magnitude of φ_i are determined so that $-180° \leqq \varphi_i \leqq 180°$, and in order to clarify how much shift the post-grinding higher harmonic phase φ'_i shows from φ_i, the sign and magnitude of φ'_i are determined so that $-180° \leqq \varphi'_i - \varphi_i \leqq 180°$. Then the relationship between φ'_i and φ_i will be shown between the $\varphi'_i = \varphi_i + 180°$ line and the $\varphi'_i = \varphi_i - 180°$ line as illustrated ir Fig. 13 (c), and the $\varphi'_i - \varphi_i$ shift will be

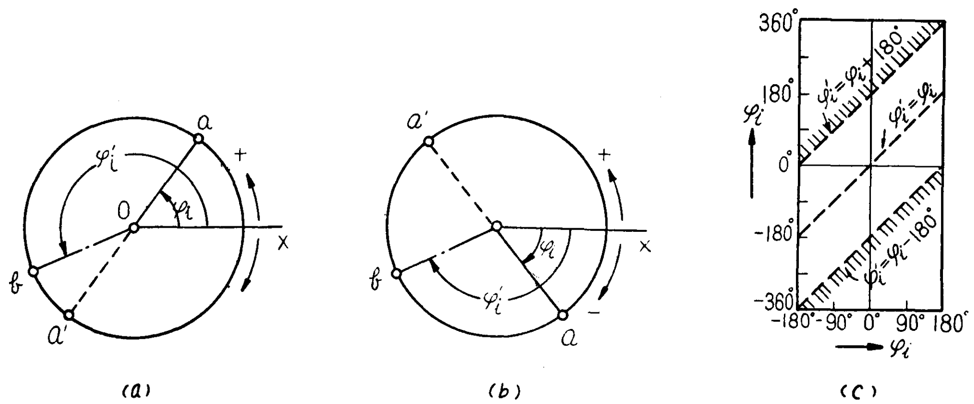


Fig. 13. (*a*), (*b*), (*c*)

seen in comparison with the standard line of $\varphi'_i = \varphi_i$. For instance, the relationship between φ_3' and φ_3 for the experiment results in Fig. 5 is shown in Fig. 14.

Comparison of Fig. 14 with the $C'_3 - C_3$ relationship in Fig. 5 shows that, when when the supporting height is larger than 0 or smaller than that, i, e., -3.5mm, there seems to be no consistent relationship between φ'_3 and φ_3.

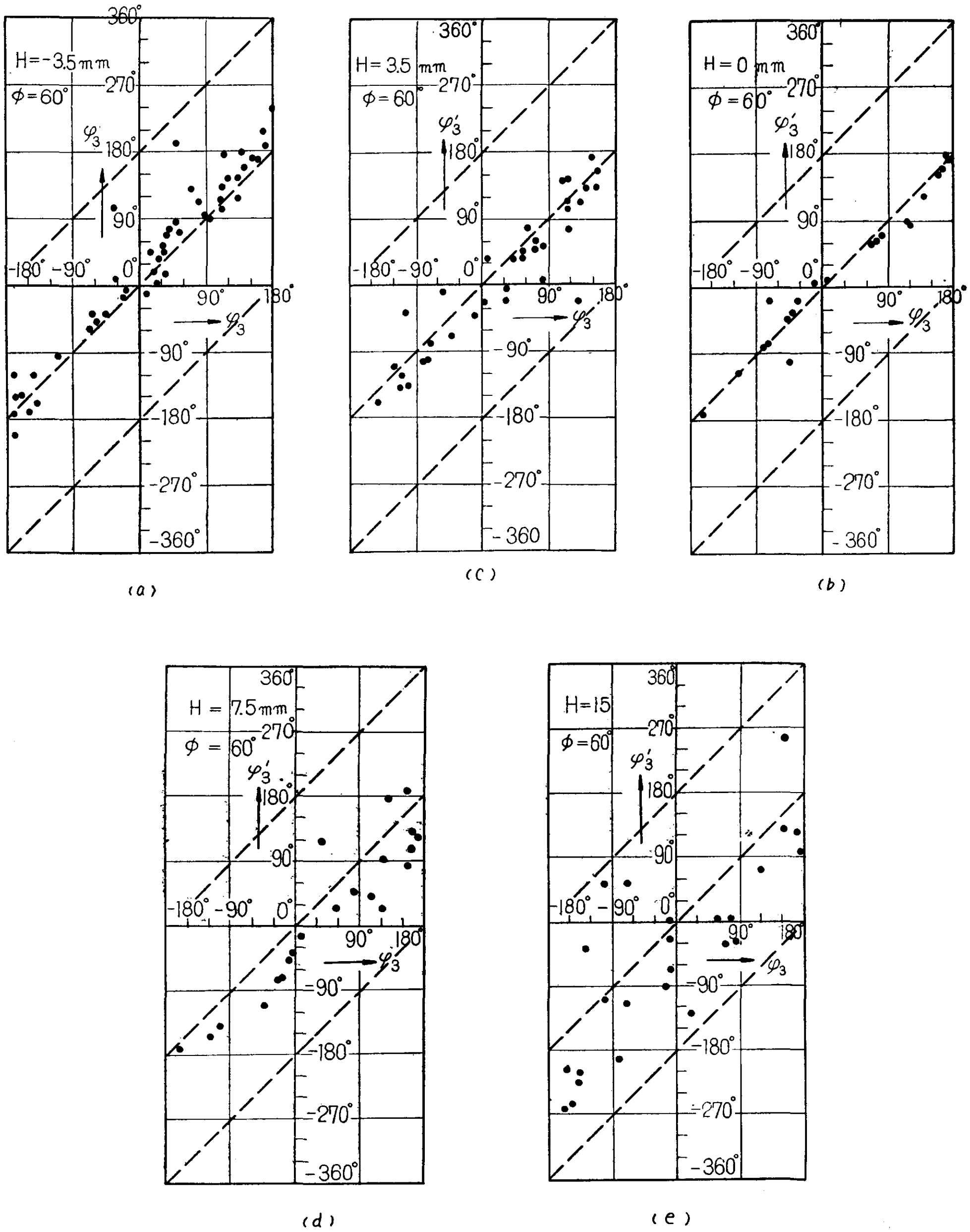


Fig. 14. (*a*), (*b*), (*c*), (*d*), (*e*)

V. Grinding conditions & higher harmonic amplitude characteristics

V. 1 Stock removal and amplitude characteristics

The reduction in the diameter of tne work, representing the depth of cut of the wheel, was set at 10, 20 and 40 μ in a series of experiments, for which yielded the C_{io} values shown in Fig. 15. Other experiments, where the diameter reduction was set at 20 and 40 μ, afforded a_i values shown in Table 2. In both cases, the experiments were conducted under constant work supporting conditions, i, e., $H=7.5$ mm and $\phi=60°$, although for the diameter reduction of 20 μ alone, the experiment results mentioned in Section 4 were used.

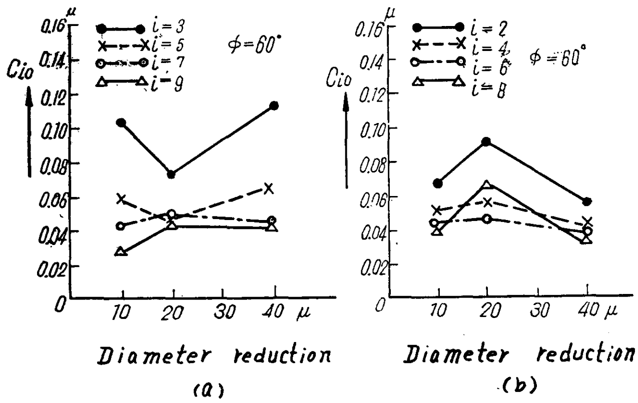


Fig. 15. (*a*), (*b*)

Fig. 15 shows that C_{io} is not much influenced by the diameter reduction except in some special cases, whereas Table 2 shows that, except in some special cases, a_i tends to decrease, though slightly, as the diameter reduction increases from 20 μ to 40 μ. However, when the diameter reduction is within the range of 10 μ $-40\,\mu$, it may be said that neither C_{io} nor a_i shows so marked variations as they do when the supporting height is varied.

Table 2

Diameter reduction	20 μ	40 μ
a_3	0. 60	0. 68
a_5	0. 63	0. 54
a_7	0. 45	0, 28
a_9	0. 19	0. 11
a_{11}	0. 12	0. 05

V. 2 Work speed and amplitude characteristics

Next, a number of experiments were conducted with the circumferential velocity V_c of the work sit at five stages, 12. 3, 21, 28. 9, 39. 8 and 56. 4 m/min.

Fig. 16 is based on these experiment results showing C_{io} values for these V_c.

Here, the grinding time was adjusted so that the total ground length would be the same for all the work specimens rotated at the various circumferential velocities, the standard being 128 rotations when V_c=28.9m/min, and the grinding time= 25 sec. Namely,

V_c (m/min) = 12.3, 21, 28.9, 39.8, 57.4
Grinding time (sec) = 58.9, 34.5, 25, 18, 18

It is seen from the above experiments that as V_c increases from 12.3m/min to 56.4m/min, C_{io} decreases for odd numbers of order except for $C_{5,0}$ for V_c = 12.3 m/min, whereas for even numbers of order C_{io} tends to increase through slightly except for $C_{2,0}$ for V_c = 12.3m/min. The $C_{5,0}$ and $C_{2,0}$ values for V_c = 12.3m/min were exceptional presumably because at this low cirumferential velocity the stock removal por rotation was large, i, e., the grinding amount for the given depth of cut was removed through through a few rotations after the begining of the grinding, so that the work slipped a little as it turned, which fact was noted in eye-observations, too.

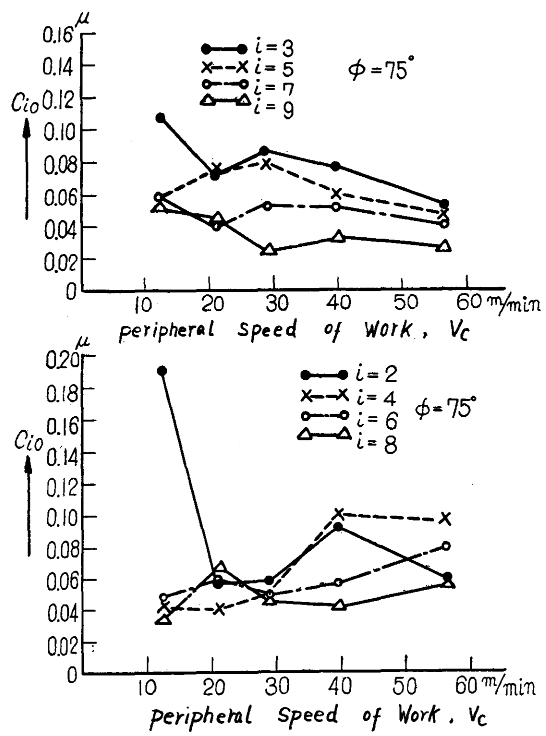


Fig. 16.

Next, specimens with comparatively large out-of-roundness were used in a series of experiments with the work speed set at three stages, 12.3, 21 and 28.9 m/min, which yielded a_i values as shown in Table 3 below:

Table 3.

V_c (m/min)	12.3	21	28.9
a_3	0.55	0.57	0.60
a_5	0.57	9.59	0.63
a_7	0.69	0.46	0.45
a_9	0.14	0.20	0.19
a_{11}	0.26	0.11	0.12

Table 3 shows that, as the work speed rises from 12.3m/min to 28.9m/min, a_i tends to increass, though slightly, except in some special cases.

VI. Conclusion

Through harmonic analysis of the pre-grinding and post-grinding outlines of the cross section of the centerless grinding work, relationships between the pre- and post-grinding values of the higher harmonic amplitudes and phases of the out-of-roundness curves as defined in chapter 3 were examined in a number of experiments. Their results may be summarized as follows;

(1) Betwen the pre- and post-grinding higher harmonic amplitudes, especially those of odd numbers of order close relationships were noted. They varied considerably according to the work supporting height.

(2) As for higher harmonic phase shifts in centerless grinding, no differencies were noted under conditions where there hardly any noticeable variations in amplitudes of odd number of order i, e., when the supporting height was 0 mm ; but when the supporting height was larger or smaller than 0 mm, the interrelationship between the pre- and post-grinding phases was lost.

(3) The grinding conditions do not exert so marked influence on the amplitude characteristics as the work supporting conditions.

Thus, by systematically studying by experiments the characteristic of centerless grinding as to the higher harmonic amplitudes, it was found that the work supporting conditions considerably affect the higher harmonic amplituees. In the next report, this writer will analyze the forming mechanism of the centerless grinding work with special attention paid to the work supporting conditions, and thereby re-examine the above expriment results.

Bibliography

(1) Centreless Grinding, Part 1 (Machimery's Yellow Back Series 9), p. 6.
(2) Cincinnati Grinders, Inc., Principles of Centerless Grinding, p. 5.
(3) W. Judge, Grinding, Lapping and Polishing, I, (1850), p. 27; II, (1950) p. 1.
(4) Nakada: Mathematical Analysis of Machines, (1951), p. 54.
(5) Soda: Friction and Lubrication, (1954), p. 8.