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Practical Application of the Sonic Testing to Determine the Grade of Grinding Wheels

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1) Introduction

A bonded abrasive is composed of abrasive grains and bonding material. As it is mostly used in the shape of a disk, the name "grinding wheel" has been used in a broad sense inclusive of a grinding stick.

Grade or hardness is one of the most important characteristics of a grinding wheel, because it is closely related to the grinding performance at work. Although numerous methods for testing grade of a grinding wheel have been in use up to now, a conclusive method has not yet been agreed upon to the satisfaction of all.

Most of grinding wheel manufacturers employ their own mechanical graders such as scratching and sand-blasting testers. In recent years the sonic method has gradually been in use, because the measuring procedure is handy and nondestructive, and the measured value has a real physical significance.

This investigation was carried out in order to handle the sonic method properly from the view of a grinding wheel manufacturer.

2) The Sonic Testings

The E-modulus of a grinding wheel can be easily measured by sonic testing devices, which are now made by a few companies in the world. These devices refer to measuring the dynamic E-modulus of a grinding wheel in spite of their different origins.

The Sonic Comparator and the Grindo-Sonic are based on detecting the natural frequency of a grinding wheel within an audible range and represent the overall characteristics of an entire test piece.

The Ultrasonic Grader is based on detecting the transmission velocity of ultrasonic pulses and represent the local characteristics in the test piece.

2-1) Sonic Comparator

This device has been developed by R.G.Rowe[1] in U.S.A. and is extensively used in grinding wheel manufacturers.

A grinding wheel in any shape has various natural frequencies of vibration. A disk and a rectangular bar vibrate in many kinds of modes as shown in Fig.1 and 2, when they are excited freely.

The Sonic Comparator makes it possible to calculate the E-modulus of a grinding wheel from any natural frequency regardless of the mode of vibration. Several physical constants except the E-modulus can be evaluated by comparing the natural frequencies of vibration for various modes. In this case, a grinding wheel in the shape of either disk or rectangular bar is supported at the nodes of a preferred mode of vibration and then excited with an exciting stylus.

In production testing, however, a fundamental diameter mode for a disk and a fundamental flexural mode for a rectangular bar are favorably used, because these modes can be more easily detected.

The natural frequency of a disk for the fundamental two-nodal diameter mode is given by the classical theory[2] as follows:

$$f = \frac{5.25\ t}{\pi D^2} \sqrt{\frac{E}{3\varphi(1-\nu^2)}} \qquad (1)$$

where
- f = natural frequency of two-nodal diameter mode
- t = thickness of the disk
- D = diameter of the disk
- E = E-modulus of the disk
- φ = mass density of the disk
- ν = Poisson's ratio of the disk

For a disk with an arbour hole, the natural frequency for the fundamental two-nodal mode is given as follows:

$$f = \left\{1 - (d/D)^2\right\} \frac{5.25\ t}{\pi D^2} \sqrt{\frac{E}{3\varphi(1-\nu^2)}} \qquad (2)$$

where d = hole diameter of the perforated disk

Eq. 1 and 2 are valid for any selfconsistent set of units.

It is said that Eq. 2 is accurate for the diameter ratio (d/D) below 1/3 and for the thickness-to-diameter ratio (t/D) below 0.15.

In case of conventional metric units, Eq. 2 can be expressed as:

$$E = 1.074 \frac{(1-\nu^2)\ f^2\ D^4 \varphi}{\left\{1-(d/D)^2\right\}^2 t^2} \cdot 10^{-12}\ \mathrm{kN/mm^2} \qquad (3)$$

where
- f = natural frequency of two-nodal diameter mode (sec^{-1})
- t = thickness of the disk (mm)

D = outer diameter of the disk (mm)
d = hole diameter of the disk (mm)
φ = mass density of the disk (g/cm^3)

Grinding wheel manufacturers are not only desirous to inspect the grade of their final products speedily but also to introduce an appropriate in-process grade inspection in order to be able to reject the off-graded wheels prior to expensive finishing and inspecting processes. For these purposes, they do not always need to know the E-moduli of their products, but it is fine to find the fluctuation of the quality in their routine processes. Therefore, the use of the frequency reading on the display panel of the Sonic Comparator offers an economic method of controlling the wheel quality. Furthermore some grinding wheel manufacturers often use a following convenient parameter instead of the frequency reading (f value).

$$k = \frac{f \cdot D^4}{W} \cdot 10^{-8} \qquad (4)$$

where W = weight of the disk (g)

For a rectangular bar, the natural frequency for the fundamental flexural mode is given by the classical theory[3] as follows:

$$f = \frac{4.73^2}{2\pi \ell^2}\sqrt{\frac{E \cdot t^2}{12\,\varphi}} \qquad (5)$$

where f = natural frequency of two-nodal flexural mode
ℓ = length of the bar
E = E-modulus of the bar
t = thickness of the bar
φ = mass density of the bar

Eq. 5 is valid for any selfconsistent set of units.
In case of conventional metric units, Eq. 5 can be expressed as:

$$E = 0.9464\,\frac{\ell^4 f^2 \varphi}{t^2} \cdot 10^{-12}\ \mathrm{kN/mm^2} \qquad (6)$$

where f = natural frequency of two-nodal flexural mode (sec^{-1})
ℓ = length of the bar (mm)
t = thickness of the bar (mm)
φ = mass density of the bar (g/cm^3)

2-2) Grindo-Sonic

This device has been developed by J.Péters and his coworkers[4] in Belgium and is used in Europe. The Grindo-Sonic is characteristic of measuring the gravest resonance frequency of the fundamental mode.

A grinding wheel is either placed horizontally on a plastic cone or on a very soft material so as to vibrate freely or left upright on the floor, and then excited with a hammer. The frequency measurement starts after a time delay, which is long enough to have the higher modes damped out. On the display panel of the Grindo-Sonic, the R value is directly seen instead of the f value. The R value corresponds to (2/f) 10 and has a dimension of the time.

All the calculations to obtain the E-modulus may be performed just as in case of the Sonic Comparator.

A.Decneut[5] proposed a more accurate equation for a thin disk with an arbour hole as follows:

$$E = \frac{P_1 \varphi D^4}{t^2 R^2} \quad kN/mm^2 \qquad (7)$$

where P = constant depending upon Poisson's ratio and the disk shape (d/D)

In case of d/D = 0, P comes to the value: 3.68.

φ = mass density of the disk (g/cm)

D = outer diameter of the disk (mm)

t = thickness of the disk (mm)

R = Grindo-Sonic reading

For a thicker perforated disk with the diameter-to-thickness ratio (D/t) below 25, Eq. 8 is given as follows:

$$E = \frac{P \varphi D^2}{R^2} \quad kN/mm^2 \qquad (8)$$

where P = constant depending upon Poisson's ratio and the disk shape (D/t and d/D)

Eq. 8 is accurate for the diameter-to-thickness ratio between 3.30 and 25.0.

He proposed a more accurate equation for a thin bar as follows:

$$E = 3.972 \, (\ell/t)^2 \, \frac{\varphi \cdot \ell^2}{R^2} \quad kN/mm^2 \qquad (9)$$

where φ = mass density (g/cm^3)

ℓ = length of the bar (mm)

t = thickness of the bar (mm)

R = Grindo-Sonic reading

For a thicker bar with the length-to-thickness ratio (ℓ/t) below 24, Eq. 10 is given.

$$E = \frac{P \varphi \ell^2}{R^2} \quad kN/mm^2 \qquad (10)$$

where P = constant depending upon the length-to-thickness ratio

2-3) Ultrasonic Grader

This device has been developed by Y.Shinozaki and his coworkers[6,7] in Japan. This is quite different in principle from the said devices. A beam of high frequency vibrations is transmitted into a grinding wheel, so that the evaluation of the wheel grade is accomplished at a given location of the grinding wheel but not as a whole.

~~The Ultrasonic Grader is based on measuring the transmitting~~ time in the following well-known equation:

$$E = \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \varphi (t/\tau)^2 \qquad (11)$$

where E = dynamic E-modulus of the grinding wheel

ν = Poisson's ratio of the grinding wheel

φ = mass density of the grinding wheel

t = thickness of the grinding wheel

τ = transmission time through the grinding wheel distance

Eq. 11 is valid for any selfconsistent set of units.

The grinding wheel is placed tightly between a transmitter and a receiver to transmit the ultrasonic waves through the wheel body. When such known constants as density, thickness and Poisson's ratio of the wheel are brought in memory of the device, the measured value on the panel is directly the E-modulus of the wheel. At present, the grinding wheel of very soft grade, very coarse grit size, highly elasticity can not be measured.

3) Effect of the Dimensional Variation of Grinding Wheels on the Sonic Reading

Grinding wheels have more or less dimensional variations, even though they belong to the same lot. These variations may occur during such processes as molding, firing (curing) and finishing. In order to apply the sonic testing to the process inspection before finishing, it is necessary to use a handy parameter which is not sensitive to the dimensional changes of grinding wheels. As regards the process inspection, the most important thing is not to find out the dimensional deviations, which can be corrected in the accompanying finishing process, but to detect the half-manufactured articles of poor qualities.

3-1) Variation in Thickness

It is evident from Eq. 1 that the resonance frequency of a grinding wheel increases with increasing wheel thickness. If the k value is adopted as a measure of the sonic hardness, we can evaluate the grade of each wheel regardless of the thickness change. These are experimentally confirmed as shown in Fig. 3.

3-2) Variation in Hole Diameter

It is obvious from Eq. 2 that the f value decreases with increasing hole diameter. However, the k value is not influenced by hole diameter as shown in Fig. 4.

3-3) Variation in Outside Diameter

As expected from Eq. 1, the f value decreases with increasing outside diameter. This is also confirmed experimentally as shown in Fig. 5. However, the diameter ratio (d/D) must not be neglected, because it influences both the f and k values.

3-4) Sonic Hardness Before and After Finishing

According to conventional mechanical grade testers, the grade of finished wheel usually differs from that of the unfinished one. Probably superficial layer of the wheel suffers some special treatment during firing (or curing) and becomes of something like a crust.

Two types of grinding wheels were tested on the Sonic Comparator before and after finishing. The analysis of variance reveals that there is no significant difference between before and after finishing, as far as the k value is concerned. This proves that the sonic method is useful for the process inspection as well.

4) Effect of the Measuring Environment on the Sonic Hardness

Vitrified bonded grinding wheels are little influenced by temperature in the open air. However, resinoid bonded wheels are so affected by both temperature and humidity in the open air, that it would be necessary to measure the sonic hardness in a constant atmosphere.

In the ordinary room condition, the k value of vitrified bonded wheels decreases only approximately 0.0025 per centigrade regardless of the type of bond, whereas that of resinoid ones decreases approximately 0.013 for a harder one.

Fig. 6 illustrates the test result performed in an artificially controlled chamber. As seen from this figure, both temperature and humidity greatly influence the sonic hardness.

For the purpose of finding the effect of aging, the test in the open air has been extended over years. The test result is shown in Fig. 7. A conventional resinoid bonded wheel is subjected to the deterioration year by year. While the silicon carbide wheel is susceptible to only temperature, the aluminum oxide one is more affected by humidity as well.

5) Sonic Hardness of Grinding Wheels

Aside from the fact that the final solution must be to know the relation of the sonic hardness to the grinding performance at work, it is desirable to begin with the comparison between the sonic hardness and other conventional mechanical hardness.

In Japan a kind of scratching hardness, called Okoshi hardness, is nationally authorized and it is related to the international hardness letter. A chisel tipped with cemented carbide is screwed down into the grinding wheel by 120 degrees under such pressure as 50 kgs for vitrified bonded wheels and 80 kgs for resinoid ones. The depth of the indentation is then measured in mm, and converted to the hardness letter from the conversion table or the graph as shown in Fig. 8.

5-1) Sonic Hardness of Vitrified Bonded Wheels

R. Snoeys and his coworkers[8,9] measured the sonic hardness of vitrified bonded wheels on the Grindo-Sonic and concluded that the E-modulus is a good measure for evaluating the wheel hardness. They investigated the relation between the E-modulus and other hardness standards, and further the influence of various wheel characteristics on the E-modulus. Their test results have an universal validity, as far as vitrified bonded wheels are concerned.

Fig. 9 shows the practical conversion graph of the k value to the hardness letter. The curves on this figure are available for most of the vitrified bonded wheels.

5-2) Effect of the Structure

The effect of the structure on the sonic values and the hardness letter are shown in Fig. 10. In addition to Okoshi hardness, the hand grade (driver hardness) by an inspector of experience is adopted.

It might be concluded from the figure that the f value would be a preferable measure of the wheel hardness, if the wheel sizes do not fluctuate, because it is not affected by the structure and comports itself just like the driver hardness.

5-3) Sonic Hardness of Resinoid Bonded Wheels

Resinoid bonded wheels vibrate with poorer resonance amplitudes. Apart from the effect of the measuring environment, these wheels are placed at a disadvantage. The grade of grinding wheels are mainly determined by both the amount of bond and the moulding density in pressing operation. The grade of vitrified bonded wheels is comparatively orderly arranged under the above recipe. In case of resinoid bonded wheels, however, the grade is determined by other complex materials such as the filler or the wetting agent too. As these constituents exist without spoiling their own properties even after curing, the sonic hardness of resinoid wheels is supposed to be more affected by veiled factors than that of vitrified ones.

If the grit sizes are plotted in the lump, there seems to show some correlation between the k value and the scratching hardness. Data for two types of preparations are shown in Fig. 11.

In order to obtain more detailed informations, bar-shaped specimens were made according to such conditions as shown in Tab. 1. The influence of various manufacturing conditions on the f value, E-modulus, bending strength and the Okoshi hardness were summerized in Tab. 2.

As to the type of abrasive grain, the white aluminum oxide wheel shows greater sonic hardness but lower scratching one. This is because the white aluminum oxide grain is more friable and has less bulk density as compared with the regular aluminum oxide one.

It is interesting that the type of bond as well as the kind of filler can be detected only by the f value.

The amount of bond, which is the sum of the powdered novolak resin and the nonvolatile part of the wetting resol resin, has a poor correlation to the sonic value, whereas it has a strong correlation to the Okoshi hardness and to the bending strength. As to the wetting agent, both the f value and the E-modulus can detect its type, whereas other scale can not.

5-4) Sonic Hardness of Other Grinding Wheels

The sonic hardness of rubber bonded wheels can be similarly measured, so far as the rubber is vulcanized into an ebonite. In case of the grinding wheels composed of thermo-plastic resins, the sonic method is not available practically.

The sonic hardness of oxychloride bonded wheels can be also measured, so far as the cement is completely hardened. The k value of a conventional oxychloride grinding wheel is very similar to that of resinoid bonded wheels as shown in Fig. 11.

The sonic hardness of such grinding wheels consisted of very fine grains as honing and superfinishing stones is performed very well. Y. Tanaka and his coworkers[10] obtained the dynamic E-modulus of honing stones by measuring the resonance frequency of ultrasonic vibration system (hone-abrasive stick). This method is interesting theoretically to study the mechanical properties of grinding wheels but supposed to have the difficulties of practical use.

6) *Conclusion*

This paper is written concerning practical applications of the sonic method to evaluate the grinding wheel hardness and not the theoretical ones. After the comparative descriptions of the measuring devices, several test results experienced in my factory are shown with the matters to be attended to apply the sonic method.

As to the possibility that the sonic hardness becomes the main current, I do not always have an affirmative conclusion, because its relevancy to the grinding performance is not clear. I am sure, however, that the handiness and the rapidiness of the sonic method will please grinding wheel manufacturers from now on.

Further investigations are at present being carried out. It is very important to supply the efficient and strong grinding wheels to the customers, so that the measurement of the E-modulus, Poisson's ratio and other mechanical constants must become more and more important. These are easily measured and confirmed by using different sonic devices comparatively.

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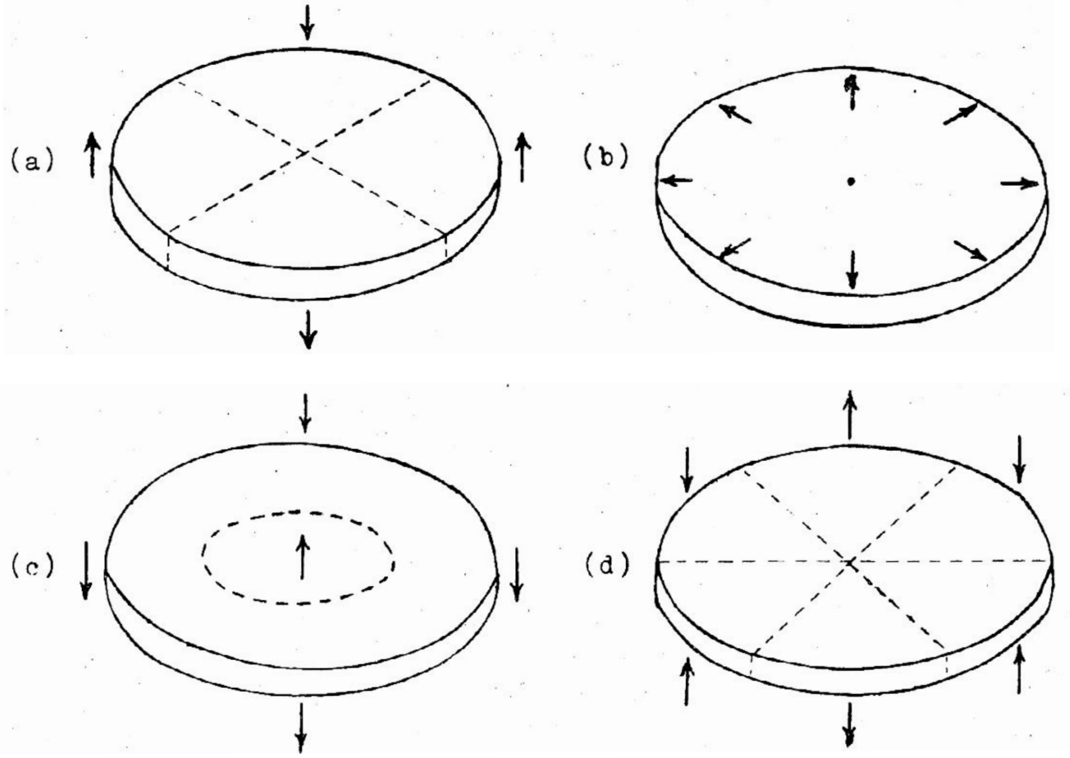

Fig. 1. Examples of vibrational modes of a thin unsupported circular disk

(a) fundamental diameter mode of vibration
(b) fundamental radial mode of vibration
(c) fundamental annular mode of vibration
(d) three-diameter mode of vibration (higher-order overtone)

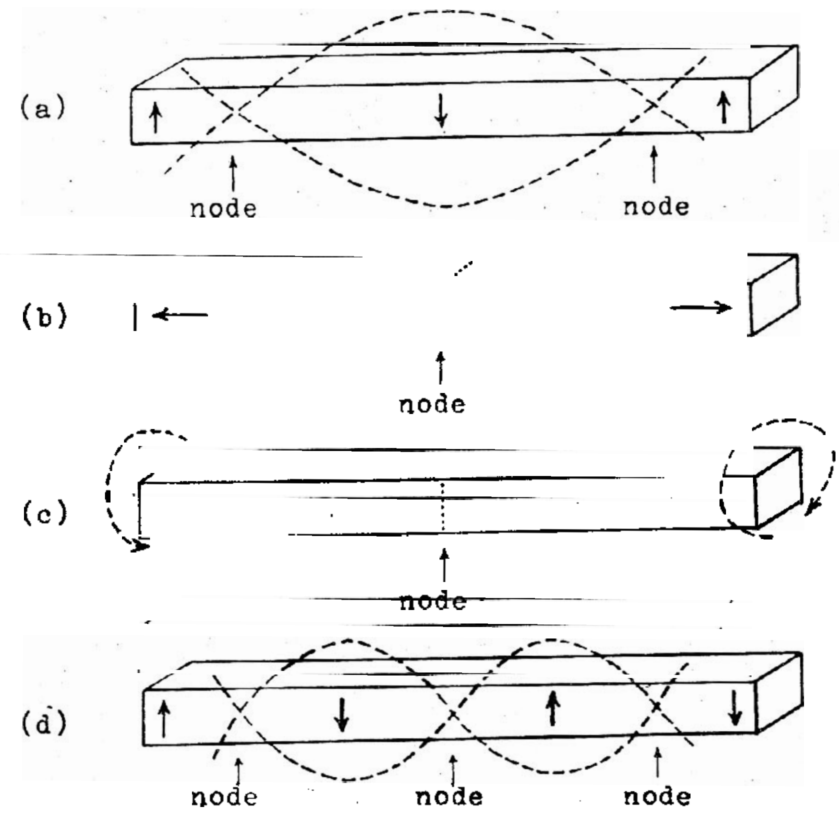

Fig. 2. Examples of vibrational modes of an unsupported rectangular bar

(a) fundamental flexural mode of vibration

(b) fundamental longitudinal mode of vibration

(c) fundamental torsional mode of vibration

(d) three-nodal flexural mode of vibration (higher-order overtone)

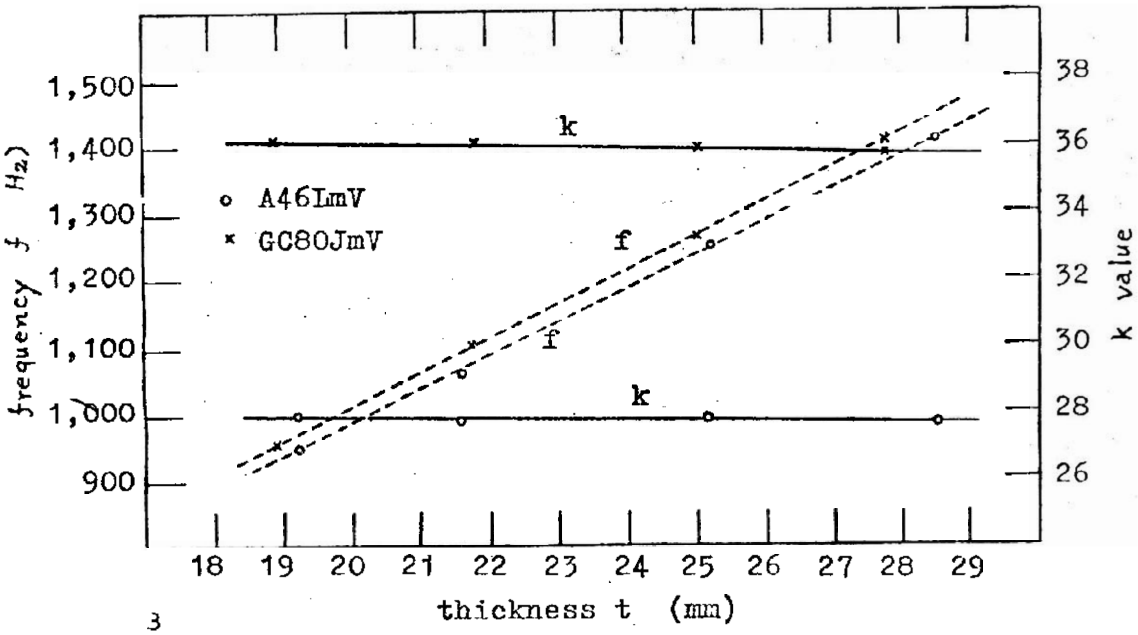

Fig. 3. Influence of thickness on sonic values.
Wheel dimensions : 305 x t x 54.5 mm

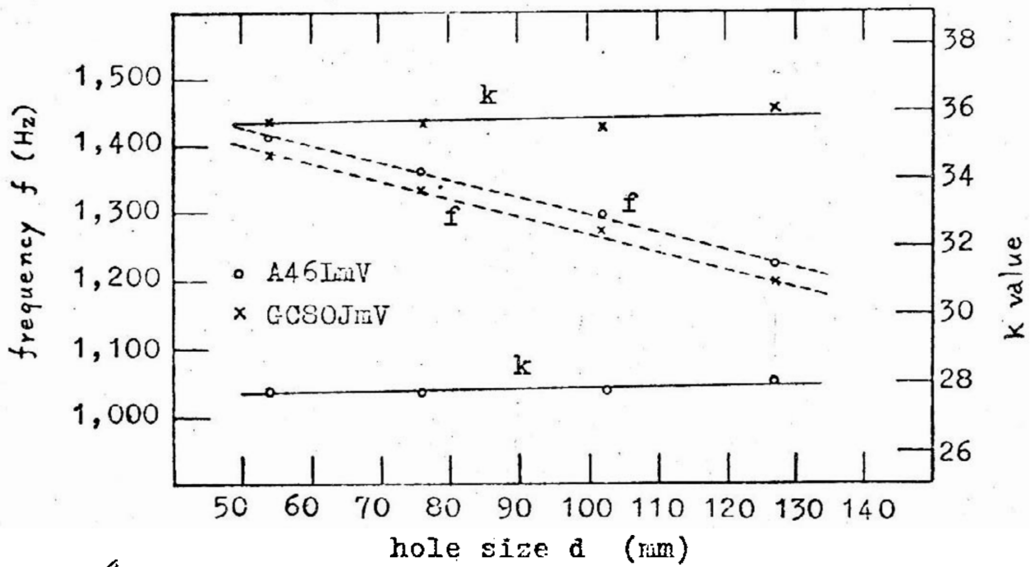

Fig. 4. Influence of hole size on sonic values.
Wheel dimensions : 305 x 28.0 x d mm

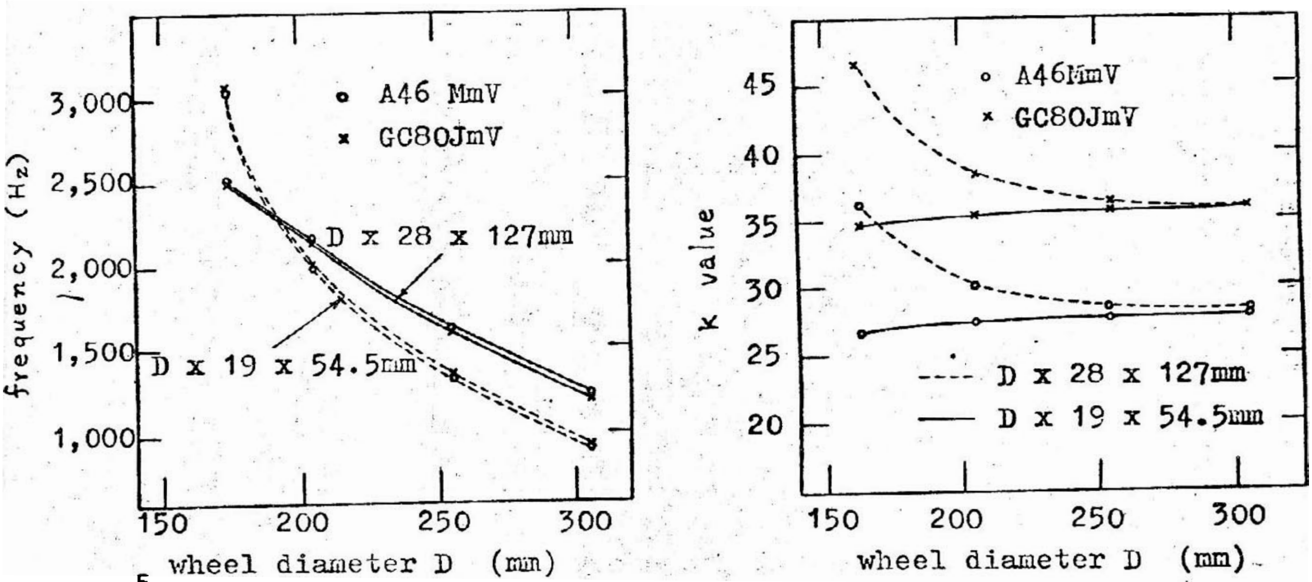

Fig. 5. Influence of wheel diameter on sonic values.
Test wheels : A46MmV, D x 28 x 127 mm and D x 19 x 54.5 mm.
GC80JmV, D x 28 x 127 mm and D x 19 x 54.5 mm.

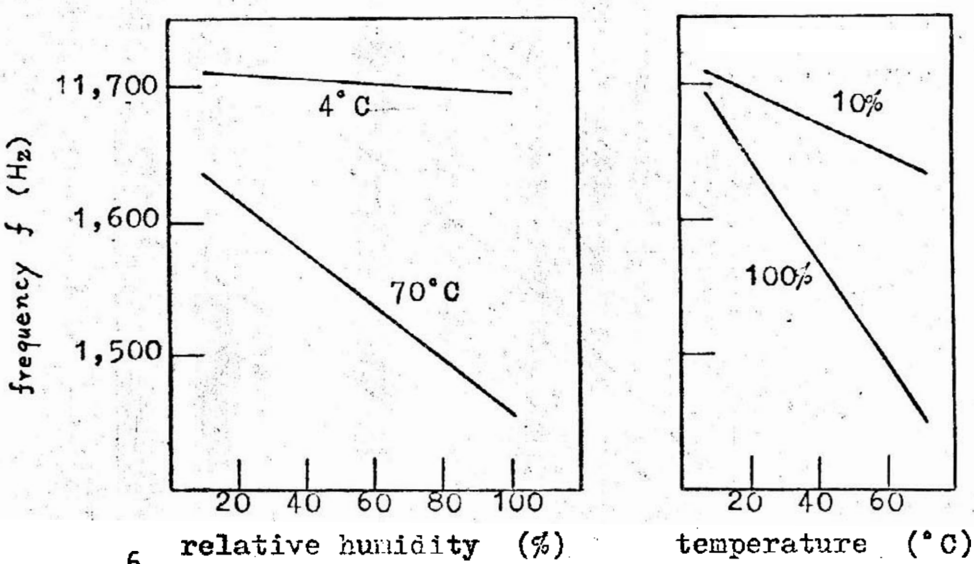

Fig. 6. Influence of atomospheric condition.
Test wheel : A30MmB, 180 x 20 x 21 mm.

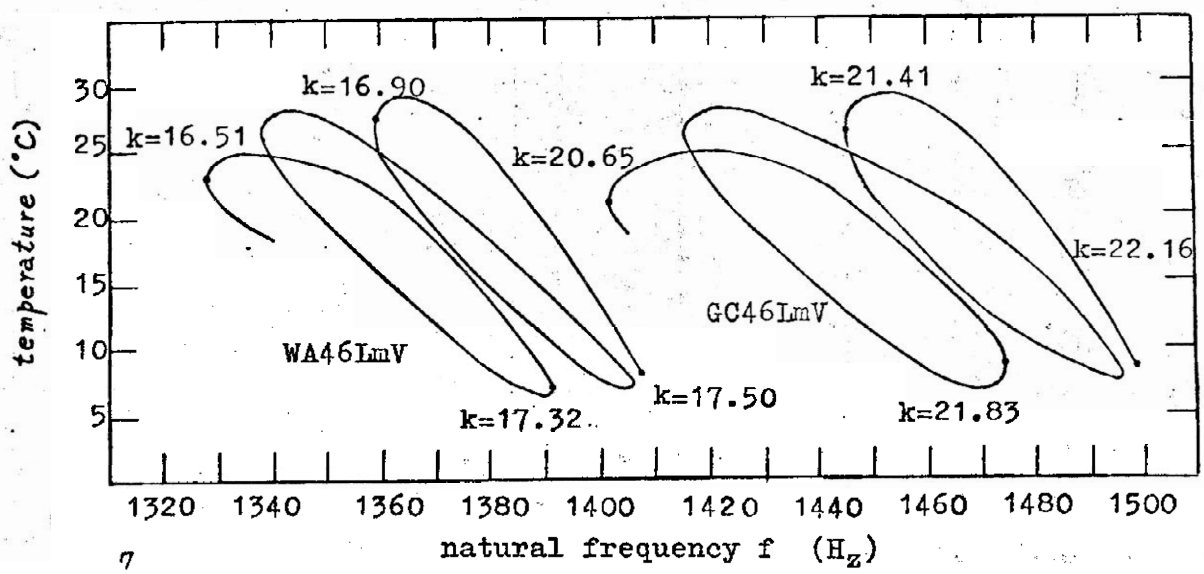

Fig. 7. Influence of aging on natural frequency of resinoid wheel.
Wheel dimensions : 195 x 19 x 50.8 mm

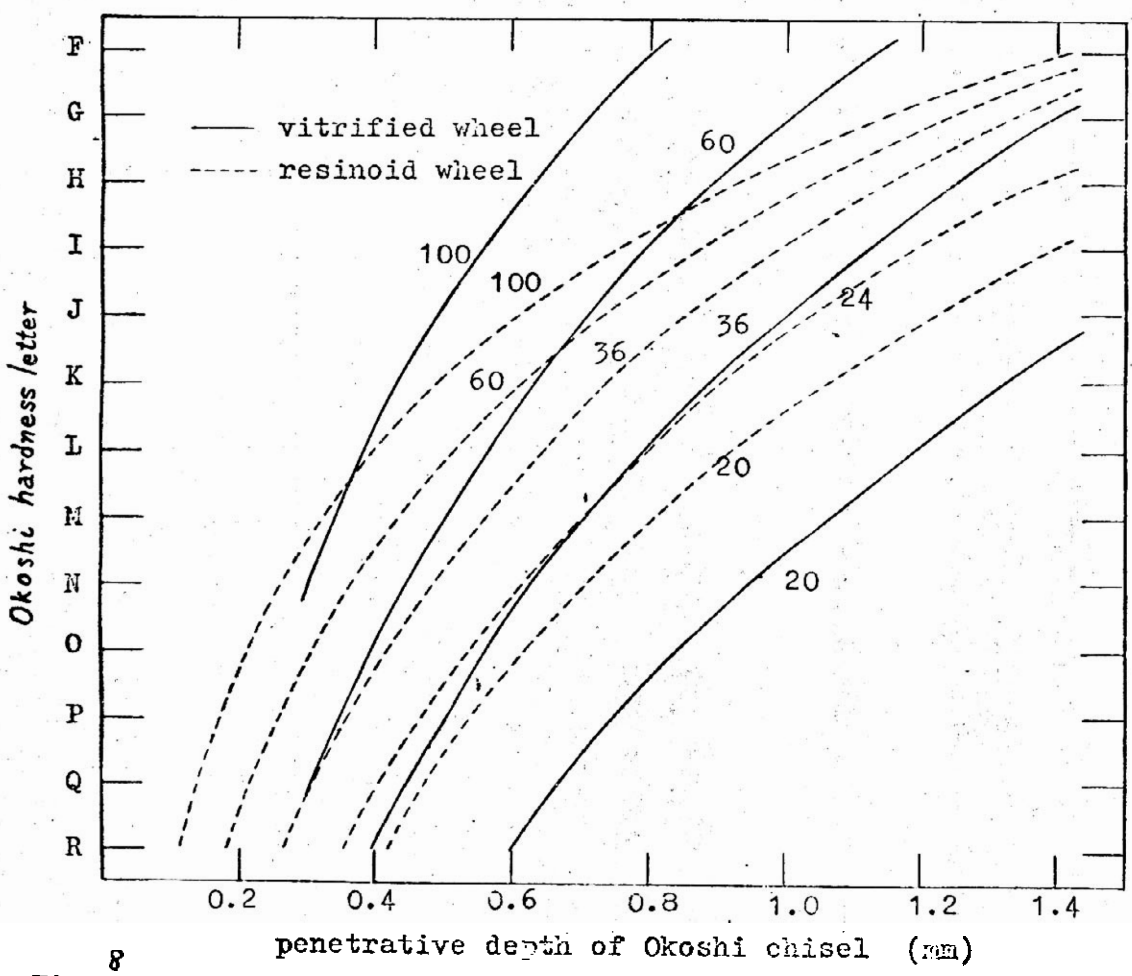

Fig. 8. Conversion graph from penetrative depth to Okoshi hardness letter.

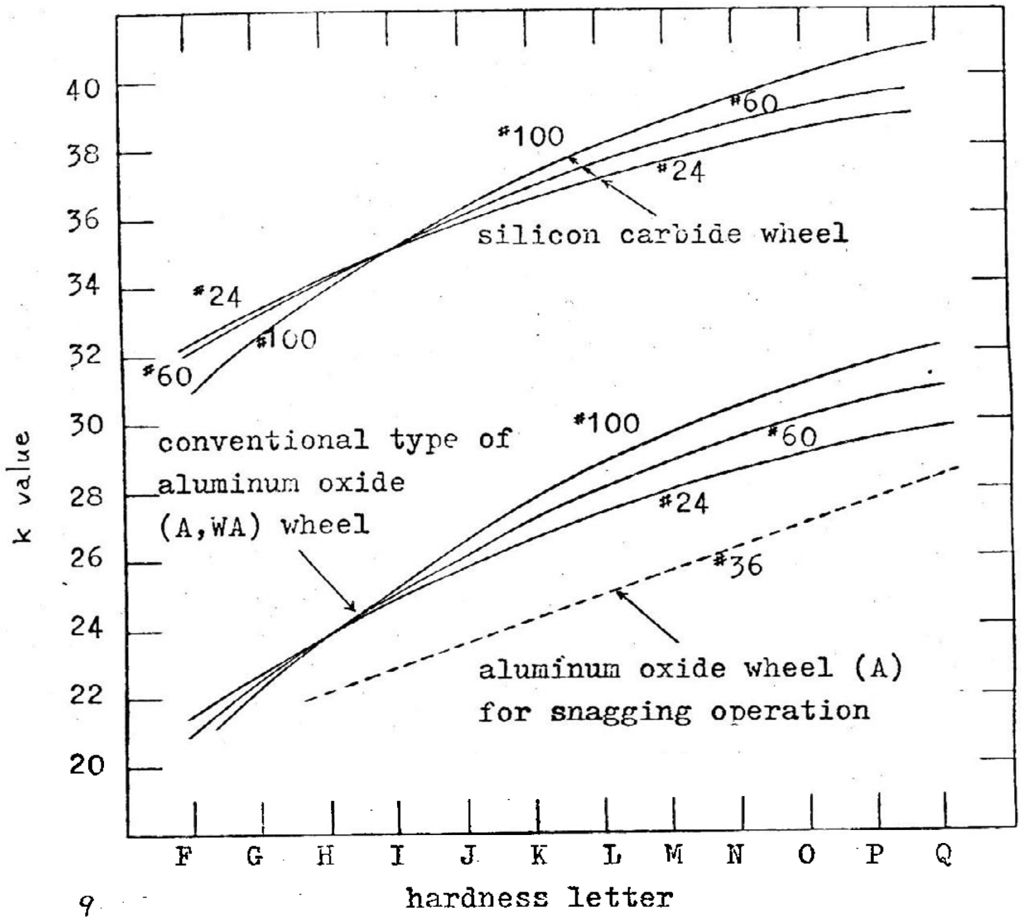

Fig. ~~12~~ 9. Conversion graph from k value to hardness letter for vitrified wheel. Loading pressure : 50 kgs.

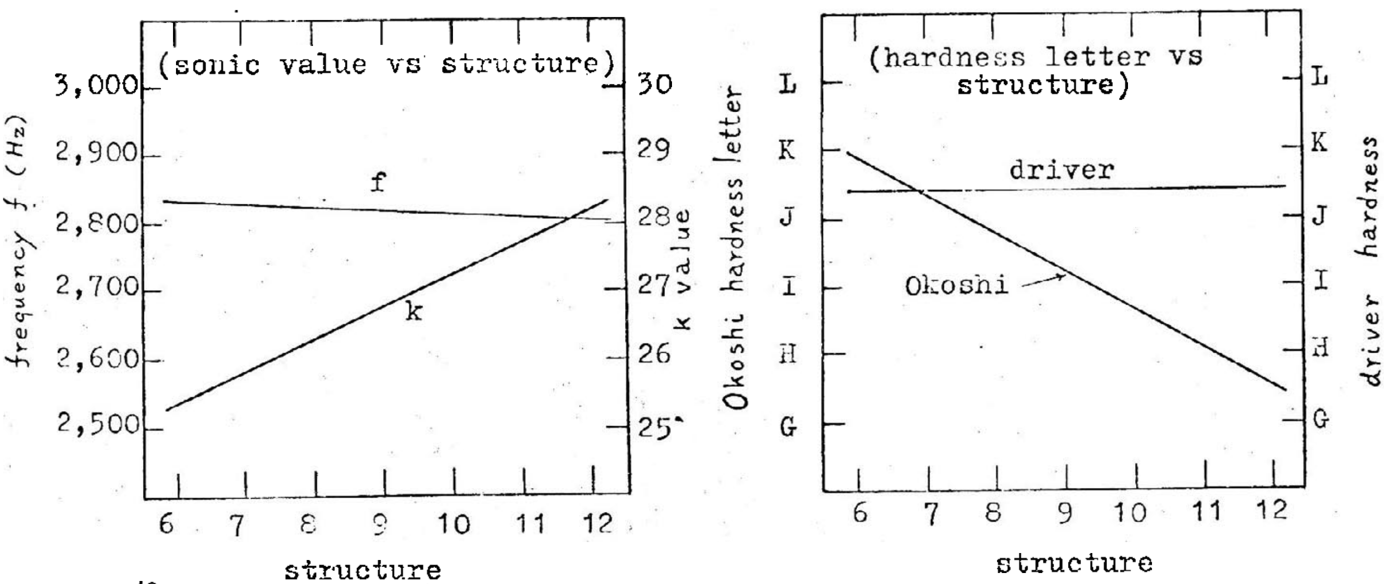

Fig. ~~13~~ 10. Effect of structure for vitrified wheel.
Test wheel : WA 60MmV, 150 x 17 x 19.05 mm

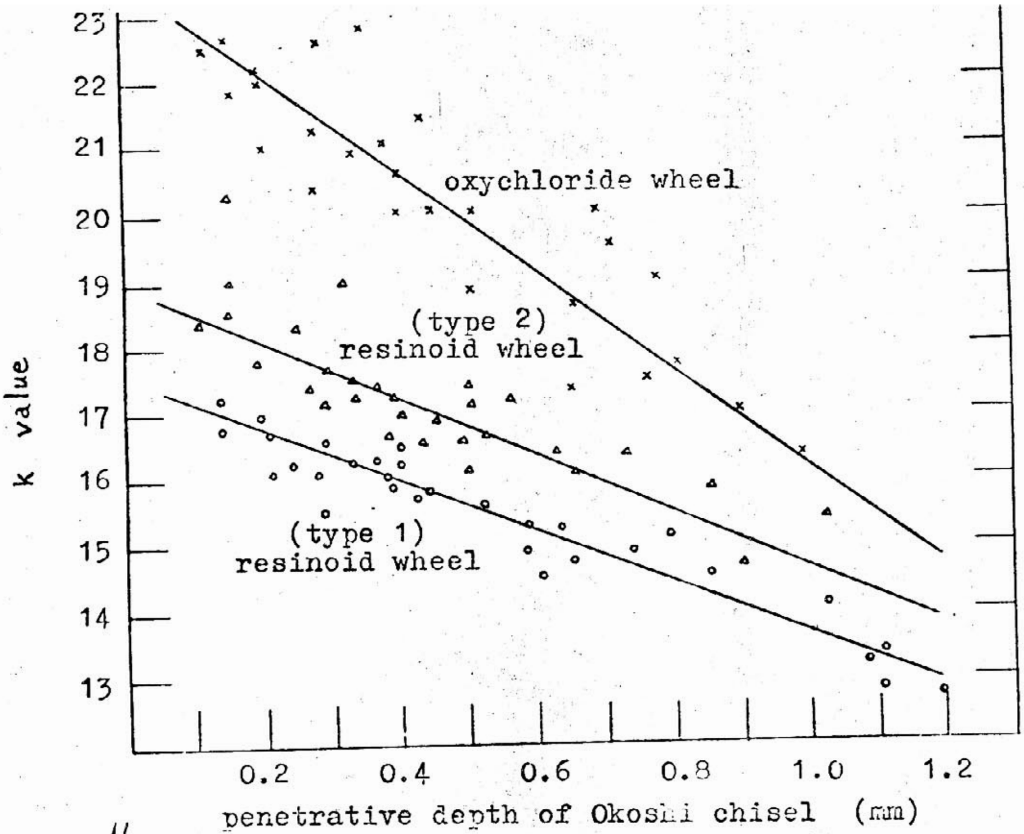

Fig. 11. Sonic value k vs penetrative depth of Okoshi hardness for resinoid and oxychloride wheels at room temperature (18°C). Loading pressure : 30 kgs.

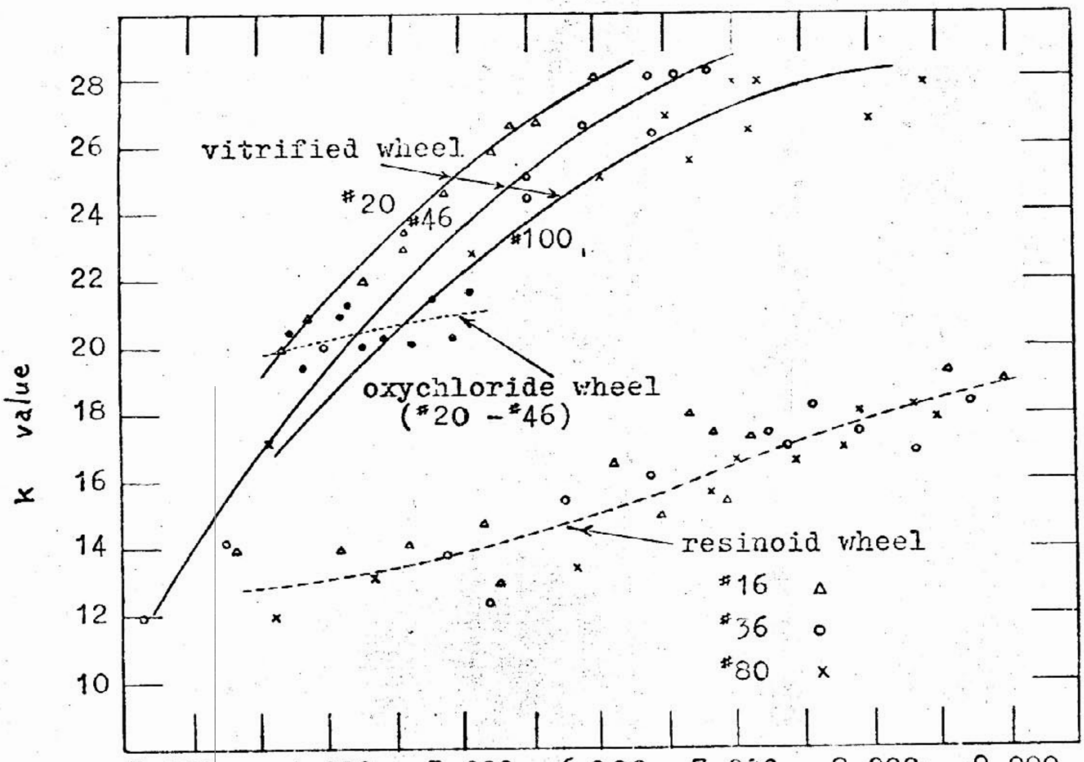

Fig. 12. Sonic value k vs bursting speed

Table 1. Experimental Layout for Resinoid Wheel to Determine the Correlation between Manufacturing Factors and Wheel Properties

Manufacturing factor	level 1	2	3
Abrasive grain	Regular A	White A	Monocrystalline A
Grit size (mesh)	24	46	100
Type of bond	KB-104	PR-359	Varcum-3337
Amount of bond (%)	12	14	16
Type of filler	Cryolite	Wollastonite	none
Type of wetter	Furfural	GP-324	MR-201
Density (g/cm^3)	2.10	2.20	2.30

Note:
The amount of bond is based on the weight of bond per hundred grain.
KB-104 represents conventional phenolic novolak resin whose melting temperature is about 90°C. PR-359 represents heat resistant novolak resin for snagging wheel and has melting temperature of approximately 96°C. Varcum-3337 represents water resistant novolak resin and has melting temperature of approximately 82°C. GP-324 represents phenolic resol resin for snagging wheel. MR-201 represents phenolic resol resin for precision grinding wheel.

Table 2. Correlation Analysis between Manufacturing Factors and Various Wheel Properties for Resinoid Wheel

Manufacturing factor	Sonic value f	Young's modulus	Bending strength	Okoshi hardness (depth)
Abrasive grain	++	+	−	+
Grit size	++	−	++	+
Type of bond	+	=	=	−
Amount of bond	−	++	++	++
Type of filler	+	−	−	−
Type of wetter	+	++	−	−
Density	++	++	++	++