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Geometric Accuracy of Workpieces in Grinding

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研削加工は，主として切削加工後の熱処理のために変形した工作物を再加工して，所定の寸法，形状を得るために行われる。従って，多くの場合，機械加工の最終工程として行われるので，研削加工後の工作物の精度は，それらを組立てることによって出来上がる各種の機械の性能に大きな影響を及ぼす。

本稿は，著者がこれまでに経験した研削加工精度に関する諸問題のうち，工学的にも興味深く，工業的にも有用と考えられるいくつかを抜出して解説したものである。これによれば，研削力に起因する加工系の弾性変影，研削熱に起因する工作物の熱変形は最も大きな誤差源である事が明らかにされている。また，加工系の弾性変影を積極的に利用する事によって加工精度を向上させる事を提案している。

1. Introduction

Grinding is usually final finishing operation for producing a machine part having required geometric accuracy such as form and size of the machine part, which has been deformed by heat treatment after cutting operation. So, a term of grinding accuracy means generally macroscopic size accuracy such as a diameter, thickness and the like, and macroscopic form accuracy such as straightness, flatness, roundness, cylindricity and the like as shown in Figs. 1 to 4.

2. Factors Affecting Geometric Accuracy of Workpieces

Relationships among factors concerning with geometric accuracies of workpieces are shown in Fig. 5. From a point of view of geometric accuracies of workpieces, major differences between grinding and cutting may be considered as follows:

2.1 Finishing process

Grinding is final finishing process for achieving required geometric accuracy of a workpiece. So, total grinding allowance is generally only in the range of 0.1 to 0.3 mm in the case of ordinary grinding operation and wheel depth of cut is only in the range of 1 to 5 μm. This value is about 1/100 of that in the case of cutting operation. Accordingly, machning accuracy required in grinding is usually about ten times as high as that in cutting.

2.2 Structure of Grinding Machine

From above mentioned reasons, the accurary required for grinding machines are very high compared with other types of machine tools. However, many types of grinding machines have unique configuration according to their functions. Consequently, effect of characteristics of grinding machines upon machining accuracies are somewhat

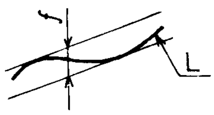

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Fig. 1. Out of straightness.

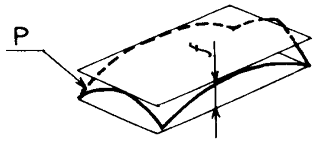

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Fig. 2. Out of flatness.

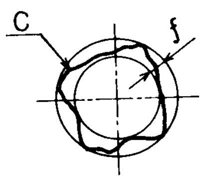

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Fig. 3. Out of roundness.

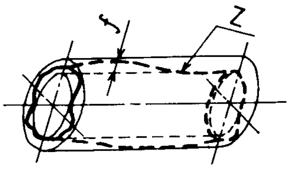

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Fig. 4. Out of cylindricity.

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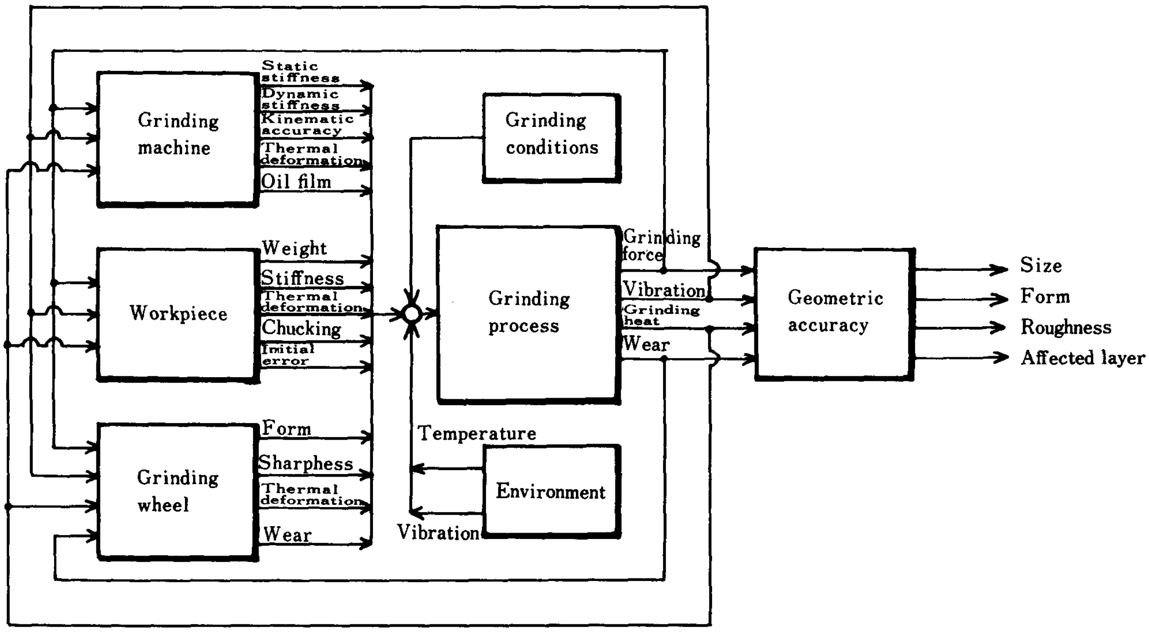
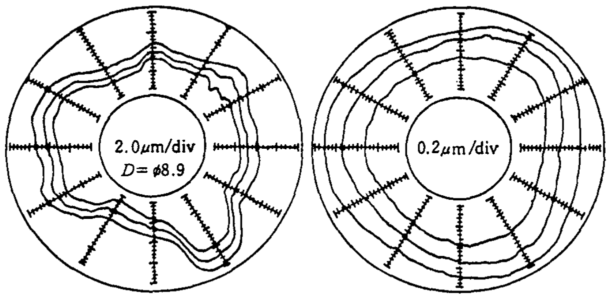


Fig. 5. Factors affecting geometric accuracy of workpieces.



(a) Center hole (b) Ground surface

Fig. 6. Roundness profiles of center hole and ground surface 1).

different from those of cuttıng machine tools because of the unique features of the grinding machines.

In the case of cylindrical grinding, for example, a slender workpice is often machined held by two dead centers. In this case, rotation accuracy of a workpiece holding system is very important because form errors of a center and a center hole are transfered to a ground surface of the workpiece as shown in Fig. 6[1].

In the case of internal grinding, effects of bending deformation due to grinding force and whirling due to unbalance of a quill are very large because the quill is very slender and rotates at very high speed.

In the case of surface grinding, the surface to be ground is always the same and the opposit surface is always a reference surface for chucking during grinding operation. Consequently, there are some problems due to such a unique machining condition.

In the case of centerless grinding, setting conditions of a grinding wheel, a regulating wheel and a work rest play a very important role in generation of a workpiece profile[2].

2.3 Grinding Heat

It is clear by observing grinding spark that a large quantity of heat generates at a contact zone of a grinding wheel and a workpiece during grinding. The heat causes sudden temperature rise near the grinding point[3] and is transferred to a workpiece, a grinding wheel and chips, and causes not only their thermal deformation but also, in an extreme case, affected layer and thermal damage on a workpiece surface.

2.4 Grinding Fluid

In order to reduce effect of grinding heat, grinding fluid or coolant is usually used. Kinds and pouring method of grinding fluid

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affect not only characteristics of a grinding wheel but also geometric accuracy of a workpiece. Properties necessary to the grinding fluid are, first of all, coolability, next, lubricatability, washability, corrosion resistance, harmlessness to an operator, etc. Grinding fluid should be selected by taking these properties into consideration.

2.5 Normal Grinding Force

In ordinary grinding operation, wheel depth of cut in one grinding pass is only 1 to 5μm. Since abrasive grains are cutting tools having a very large negative rake angle, characteristics of grinding forces are remarkably different from those of cutting forces. In the case of cutting, ratio of trangential cutting force to normal cutting force is generally about 3:1.

In the case of grinding, however, the ratio of tangential grinding force to normal grinding force is generally about 1:2[4]. This means that action of making a workpiece separate from a tool elastically is about 10 times as large as that in the case of cutting and produces comparatively large size and form errors of a woorkpiece. In addition, such large normal grinding force applied to the workpiece as a compression force causes large residual stress or mechanical damages near the ground surface together with grinding heat.

2.6 Special Features of Grinding Wheel

A grinding wheel, which is made of hard and brittle abrasive grains distributed uniformly at adequate intervals, is used in grinding as a tool in order to easily remove hard material which can not be removed with ordinary cutting tool. Since a machined surface is formed with many grooves produced by passing of individual abrasive grains, size, shape and distribution of the abrasive grains affect grinding accuracy. Degree of multiple overlapping of the grooves on a workpiece surface depends upon wheel speed, workpiece speed, depth of cut, feed rate, number of grinding pass over a point of workpiece surface, etc.

Wear of a grinding wheel is very large compared with that of a cutting tool. Self-sharpening action of the grinding wheel due to wear of abrasive grains is one of merits of grinding operation. From the standpoint to secure geometric accuracy of a workpiece, however, wear of the grinding wheel is one of weak points. Size of the workpiece will be larger than the expected value by the amount of the wear of the wheel.

On the contrary, a diameter of a grinding wheel increases slightly under certain circumstances because of loading of the wheel, and size of the workpiece will be smaller than the expected value.

Since conditions of abrasive grains on a working surface of a grinding wheel affect grinding performance, it is necessary to perform dressing and truing actively without waiting self-sharpening of the grinding wheel. It should be noted that conditions of dressing and truing play an important part in geometric accuracy of a workpiece.

2.7 Balancing of Grinding Wheel

In grinding, high rotational speed of a grinding wheel is necessary for getting adequate peripheral wheel speed. Consequently, even minute unbalance of a grinding wheel spindle system causes comparatively large whirling of a grinding wheel and vibration of the grinding machine itself.

Figure 7 shows an example of amplitude spectrum of a horizontal spindle-reciprocating

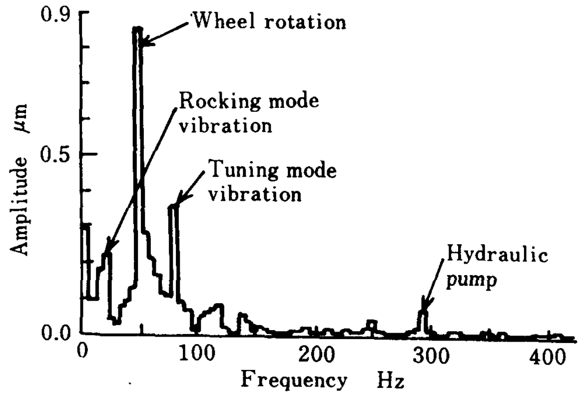

Fig. 7. Amplitude spectrum during surface grinding 5).

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table type surface grinding machine during grinding operation. It is seen that a vibration component due to wheel unbalance is the largest among many components in the case of conventional static wheel balancing which is performed off the machine[5]. Further investigations show that, far from reducing whirling of the wheel spindle, such conventional static wheel balancing deteriorates the original balance of the wheel spindle itself of the grinding machine contrary to general expectation[6),7)]. Consequently, it is seen that in-situ wheel balancing is indispensable in grinding operation.

3. Relation between Grinding Force and Machining Accuracy

Many engineers and researchers often consider that effect of grinding force upon machining accuracy is small because grinding belongs usually in a category of light cutting. However, effect of grinding force upon machining accuracy is actually very serious because required machining accuracy is very high in grinding and, in addition, the ratio of normal grinding force to tangential grinding force is high compared with cutting as mentioned in paragraph 2.

Figure 8 shows a traverse grinding system schematically as a simple elastic system. An elastic element includes not only elasticity of a grinding machine but also elasticity of all a workpiece, a fixture, a grinding wheel, etc. Refering to the figure, the following relationships are obtained:

$$F_n = c\delta \qquad (1)$$

$$= k\varepsilon \qquad (2)$$

$$\Delta = \delta + \varepsilon \qquad (3)$$

$$\varepsilon/\delta = c/k = \alpha \qquad (4)$$

where F_n is normal grinding force, Δ is set value of wheel depth of cut, ε is residual wheel depth of cut due to elastic deformation of the grinding system, δ is actual wheel depth of cut, k is a spring constant of the

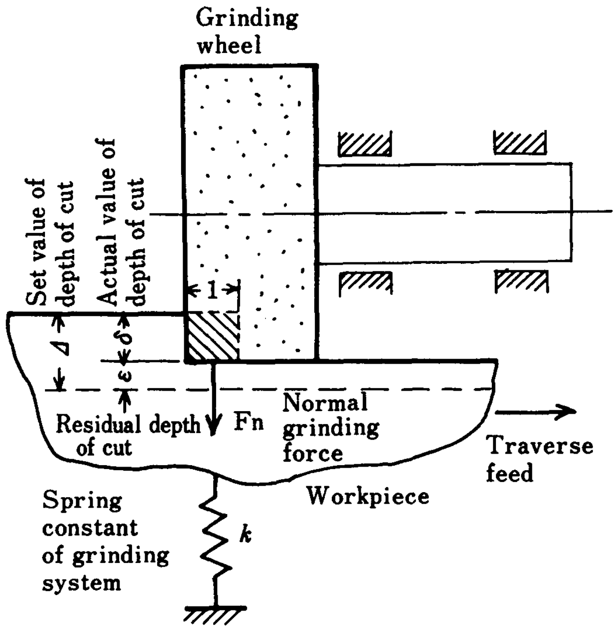

Fig. 8. Traverse grinding system.

grinding system, c is a constant representing a ratio of normal grinding force to actual depth of cut, which is sometimes called "grinding stiffness" because of its dimension, α is a constant representing a ratio of the spring constant k to the grinding stiffness c.

On the basis of the abovementioned relationships, accumulated actual depth of cut δ_i after i-th traverse stroke with the set value of wheel depth of cut Δ per a stroke is given as

$$\delta_i = \left\{1 - \left(\frac{\alpha}{1+\alpha}\right)^i\right\}\Delta \qquad (5)$$

Furthermore, accumulated actual depth of cut after j-th additional sparking-out traverse stroke is given as

$$\delta_{ij} = \left(\frac{\alpha}{1+\alpha}\right)^j \left\{1 - \left(\frac{\alpha}{1+\alpha}\right)^i\right\}\Delta \qquad (6)$$

Consequently, reduction of the workpiece radius y_{ij} is given as

$$y_{ij} = i\Delta - \alpha\left\{1 - \left(\frac{\alpha}{1+\alpha}\right)^i\right\}\left(\frac{\alpha}{1+\alpha}\right)^j \Delta \qquad (7)$$

Relationship of Eq. (7) is illustrated in Fig. 9[8]. This relation seems rather complicated.

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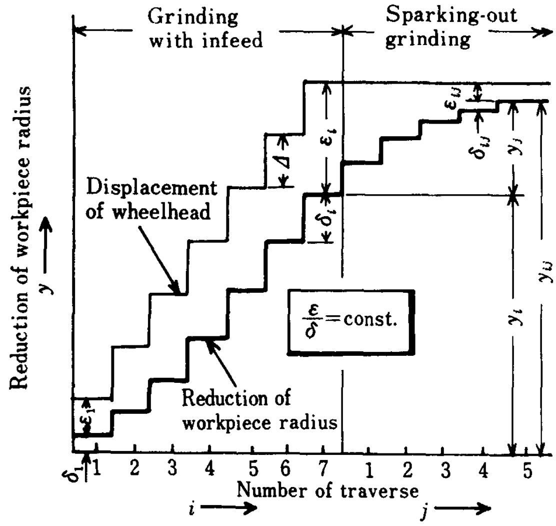

Fig. 9. Reduction of workpiece radius during traverse grinding[8].

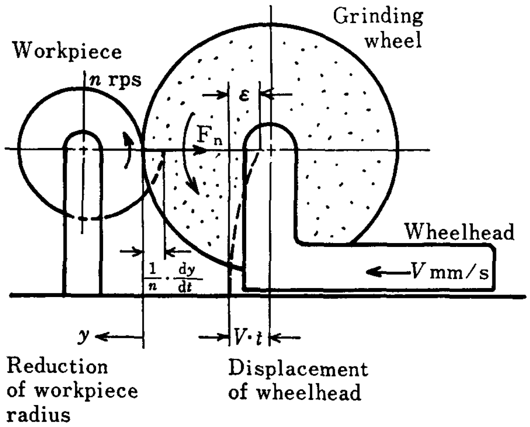

Fig. 10. Plunge grinding system.

However, a law governing the whole process is only that ε/δ is always constant, and can be easily understood.

In traverse grinding, degree of improvement of profile errors is represented by

$$\xi=\left(\frac{\alpha s}{1+\alpha s}\right)^{i} \tag{8}$$

where s is a feed of traverse[9]. Degree of increase of residual depth of cut is given by

$$\zeta=\alpha\left\{1-\left(\frac{\alpha s}{1+\alpha s}\right)^{i}\right\}. \tag{9}$$

Figure 10 shows a cylindrical plunge grinding system schematically. Refering to the figure, the following relations can be obtained.

$$F_n=\frac{1}{cn}\frac{\mathrm{d}y}{\mathrm{d}t} \tag{10}$$

$$=k\varepsilon \tag{11}$$

where y is reduction of workpiece radius, n is rotational speed of a workpiece, F_n is normal grinding force, c is grinding stiffness, k is stiffness of a grinding and ε is residual depth of cut due to elastic deformation of the grinding system.

During infeed grinding period, ε can be written as

$$\varepsilon=Vt-y \tag{12}$$

where V is infeed rate in plunge grinding.

During sparking-out grinding period, ε can be written as

$$\varepsilon=A-y \tag{13}$$

where A is a total feed given to a wheelhead during the infeed grinding period.

From Eqs. (10) to (13), the following relation ships can be obtained.

$$\frac{\mathrm{d}y}{\mathrm{d}t}=\frac{nk}{c}(Vt-y) \tag{14}$$

for infeed grinding period and

$$\frac{\mathrm{d}y}{\mathrm{d}t}=\frac{nk}{c}(A-y) \tag{15}$$

for sparking-out grinding period.

By solving these equations under the initial conditions of $y=0$ at $t=0$, reduction of the workpiece radius y is written by

$$y=Vt-\frac{Vc}{nk}\left\{1-\exp\left(-\frac{nkt_1}{c}\right)\right\}\exp\left(-\frac{nkt_2}{c}\right) \tag{16}$$

where t_1 is time duration of infeed grinding period and t_2 is time duration of sparking-out grinding period. Since Eq. (16) represents the same physical meaning as Eq. (7), both equations are identical.

Figure 11 illustrates the relation among y, t, t_1 and t_2 shown in Eq. (16)[10),11)]. Such

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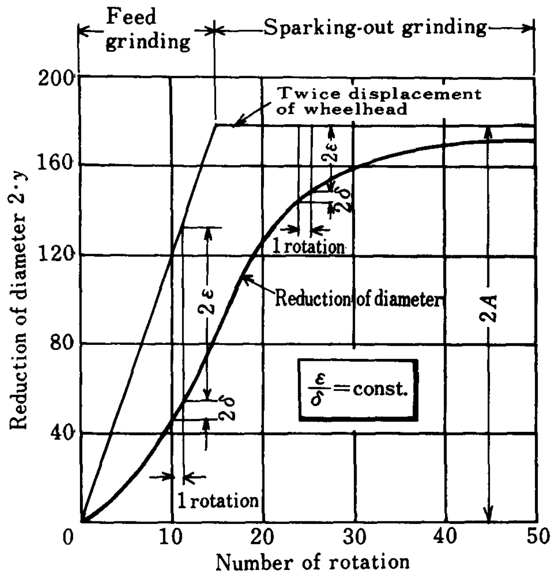

Fig. 11. Reduction of workpiece diameter during plunge grading[10].

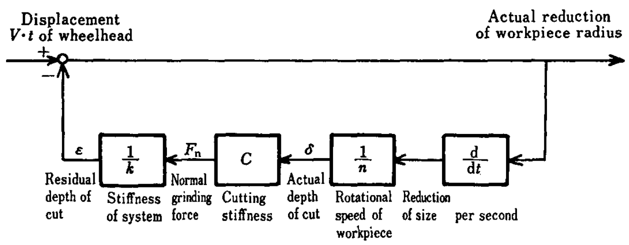

Fig. 12. Block diagram of elastic plunge grinding system.

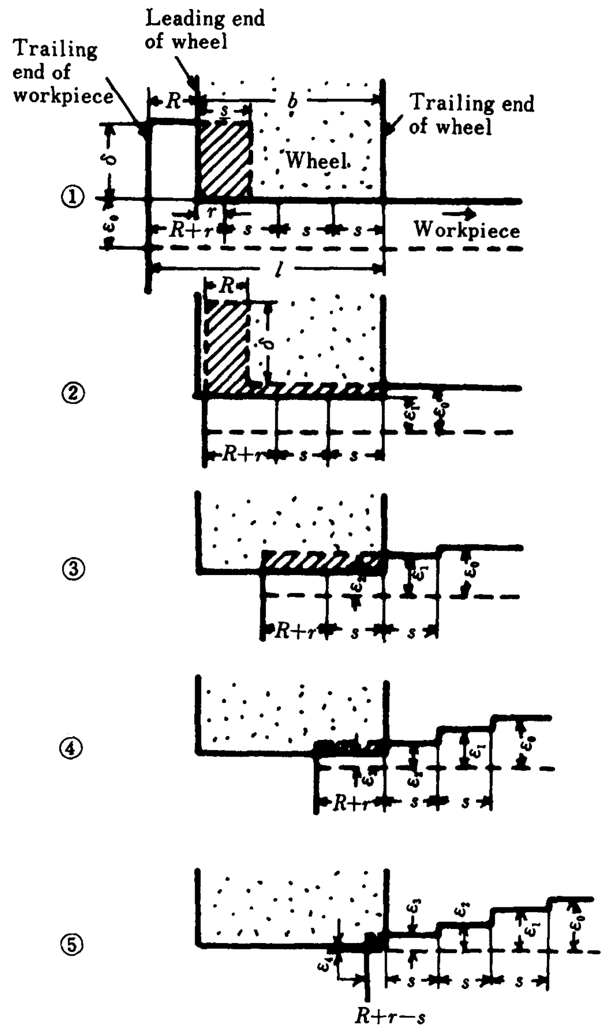

Fig. 13. Generating mechanism of undersized tapered portion at workpiece end[9].

characteristics of a grinding system as deformed by normal grinding force can be easily understood by using a block diagram as shown in Fig. 12.

In grinding operation, residual depth of cut produced by normal grinding force is considerably large compared with the required accuracy as above-mentioned. Consequently, as the leading edge of the grinding wheel overruns beyond the end of the workpiece, the elastic deformation of the grinding system will recover and the residual depth of cut will decrease. So, an undersized tapered portion is always produced at the end of the workpiece as shown in Fig. 13. Width of the undersized tapered portion in grinding is not so narrow as that in cutting and ranges to the width of the grinding wheel. Consequently, comparatively large form errors are produced, such as out of cylindricity in the case of external and internal cylindrical grinding, and out of straightness and flatness in the case of surface grinding.

In order to avoid such an undersized, tapered portion, it is necessary to distribute residual depth of cut uniformly over the surface to be machined by controlling recovery of accmulated elastic deformation through so-called tarry or dwell motion without overrun of the wheel from the workpiece end as shown in Fig. 14.

It is well known that grinding force is ap-

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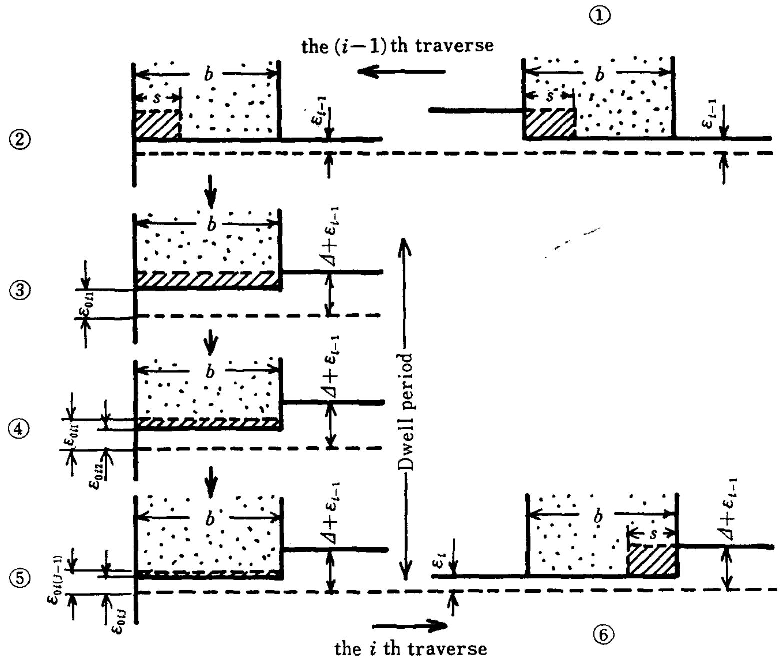

Fig. 14. Principle of tarry motion[9].

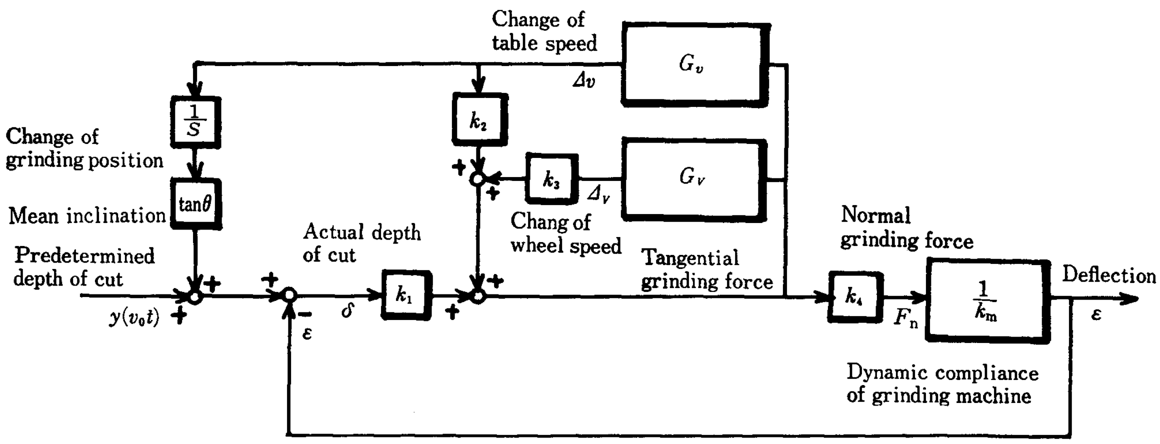

Fig. 15. Surface grinding system taking speed change into consideration[12].

proximately proportional to peripheral speed v of a workpiece and inversely proportional to peripheral speed V of a grinding wheel as shown in the following expression.

$$F_n \propto v/V\,. \qquad (17)$$

Consequently, if these speed v and V vary during grinding operation according to grinding force, the speed variation will be fed back to the grinding force. As a result, the elastic deformation of the grinding system varies according to the speed variation and machining errors are produced. For example, in a horizontal spindle-reciprocating table type surface grinding machine, grinding process is performed intermittently. Consequently, grinding force varies stepwise and speed of a grinding wheel drive system and a work table drive system are affected.

Figure 15 shows a block diagram of a surface grinding system taking the speed variation into consideration. In a wheel drive

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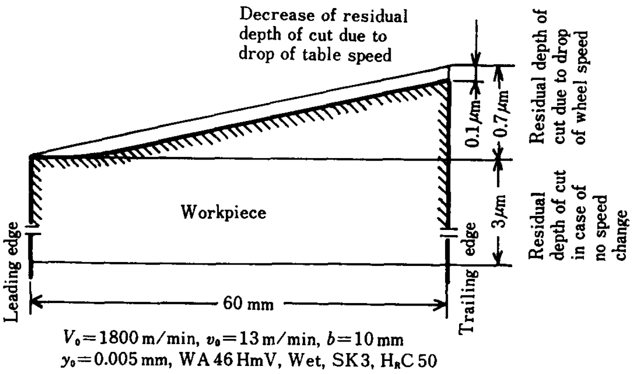
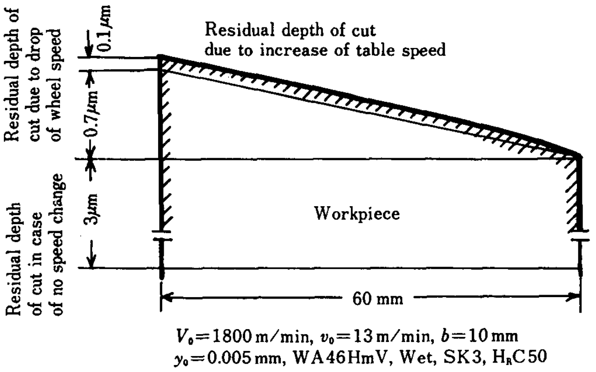


(a) Up-cut grinding



(b) Down-cut grinding

Fig. 16. Workpiece profile in one pass surface grinding[12].

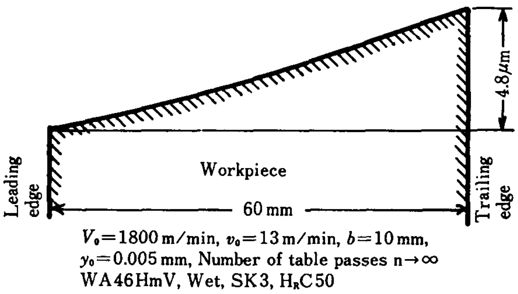


Fig. 17. Workpiece profile in uni-direction surface grinding[12].

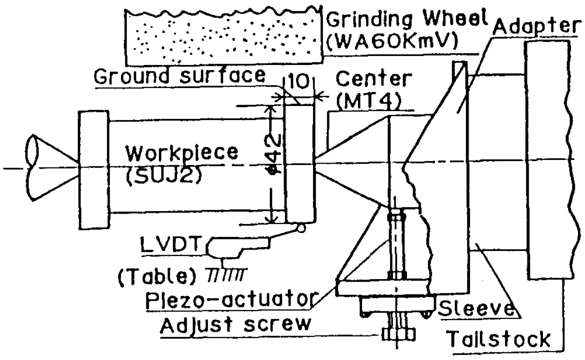


Fig. 18. Device for controlling depth of cut in cylindrical grinding[13].

system, wheel speed V drops after start of grinding according to tangential grinding force F_t. On the other hand, in a table drive system, table speed v drops after start of grinding in an up-cut stroke and rises contrariwise in a down-cut stroke according to tangential grinding force F_t.

Figure 16 shows an example of form errors due to speed variation. Increase of the grinding force due to the drop of the wheel speed V makes residual depth of cut increase. Since the increase of the residual depth of cut is positively fed back to the expected depth of cut, actual grinding force becomes larger than the expected value. Consequently, thickness of the workpiece becomes larger than at the trailing end than at the leading end of the workpiece.

On the other hand, the table speed v drops in an up-cut stroke, and rises in a down cut stroke according to tangential grinding force. Accordingly, the residual depth of cut decreases in the up-cut stroke and increases contrariwise in the down-cut stroke.

In reciprocating table type surface grinding, since the inclination of a workpiece due to the drop of the wheel speed reverses its direction every stroke, the form error cancels each other and does not accmulate so large. However, if grinding pass is repeated in the same direction like rotary table type surface grinding, the inclination of the workpiece is accmulated and increases upto considerably large amount as shown in Fig. 17.

As above-mention, elastic deformation of a grinding system is one of the major sources of geometric errors of ground workpieces. However, it is possible to actively utilize the elastic deformation of a grinding system itself for improving machining accuracy.

Figure 18 shows a device for controlling

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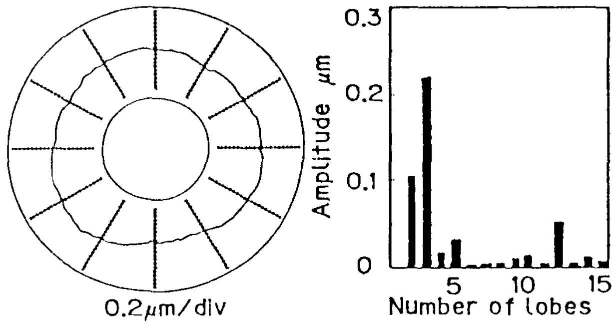
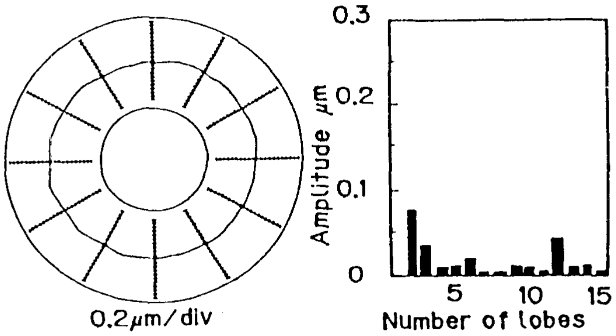


(a) Conventional grinding



(b) Controlled grinding

Fig. 19. Comparison of roundness of ground workpiece[13].

actual depth of cut precisely in cylindrical grinding by using a piezo actuator in order to compensate out of roundness of a ground workpiece caused by form errors of a dead center and a center hole[13]. Effect of this device is shown in Fig. 19. It is seen that two and three lobe components of the roundness in a circle which are usually dominant in ordinary cylindrical grinding can be reduced remarkably.

4. Relation between Grinding Heat and Machining Accuracy

Heat Q_0 generated by mechanical work done during grinding process can be written as

$$Q_0=\frac{1}{J}F_t(V\pm v)\tau \doteqdot \frac{1}{J}F_t V\tau \qquad (18)$$

where J is mechanical equivalent of heat, F_t is tangential grinding force, V is peripheral speed of a grinding wheel, v is peripheral speed of a workpiece, τ is grinding time, + is used in the case of up-cut grinding pass and − is used in the case of down-cut grinding pass. The heat Q_0 should be transfered to a workpiece, a grinding wheel and chips. According to a former study[4], it is seen that about 80% of the generated heat is transfered to the workpiece and causes thermal deformation and damage of the workpiece.

The most peculiar feature of the thermal deformation of a workpiece can be seen in the case of surface grinding. In surface grinding, the surface to be ground is always the same. So, temperature of the surface being ground is usually higher than that of the bottom reference surface. Provided that 80% of generated heat is transfered to the workpiece through the grinding point, temperature distribution of the workpiece can

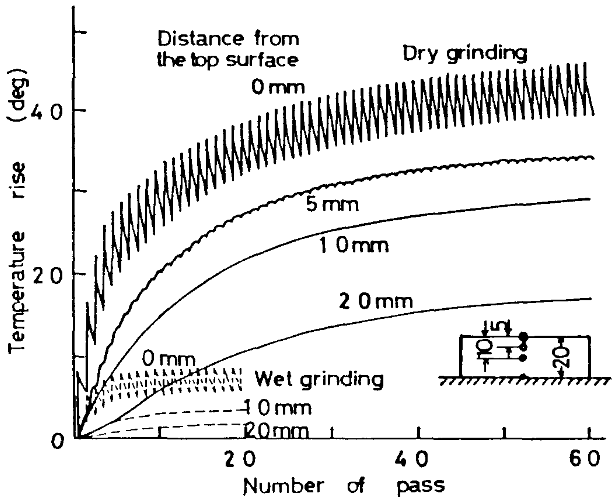


Fig. 20. Temperature variation of workpiece during surface grinding[14].

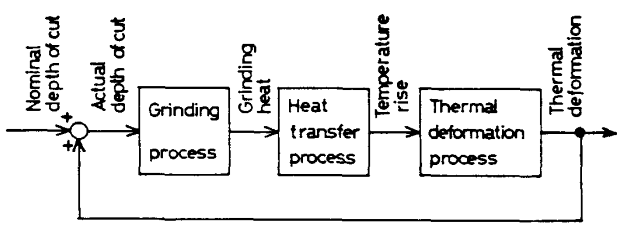


Fig. 21. Grinding system taking thermal deformation of workpiece into consideration[14].

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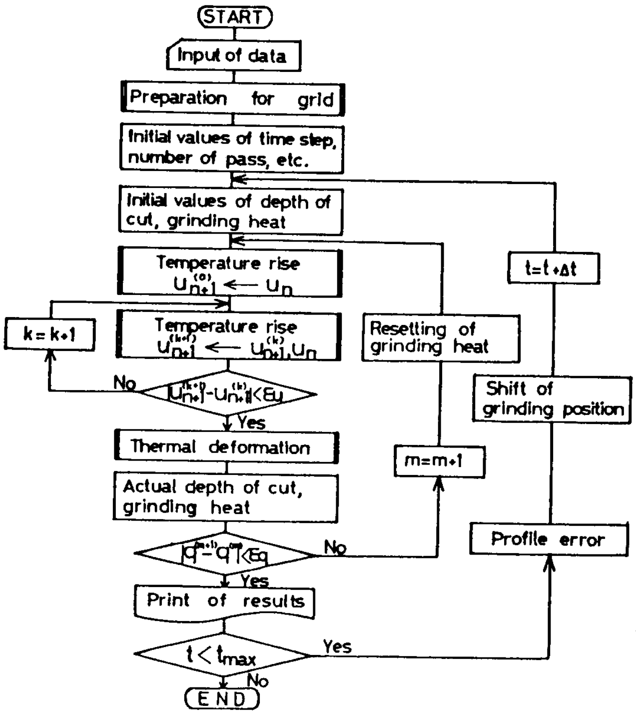

Fig. 22. Calculation of thermal deformation of workpiece in surface grading[14].

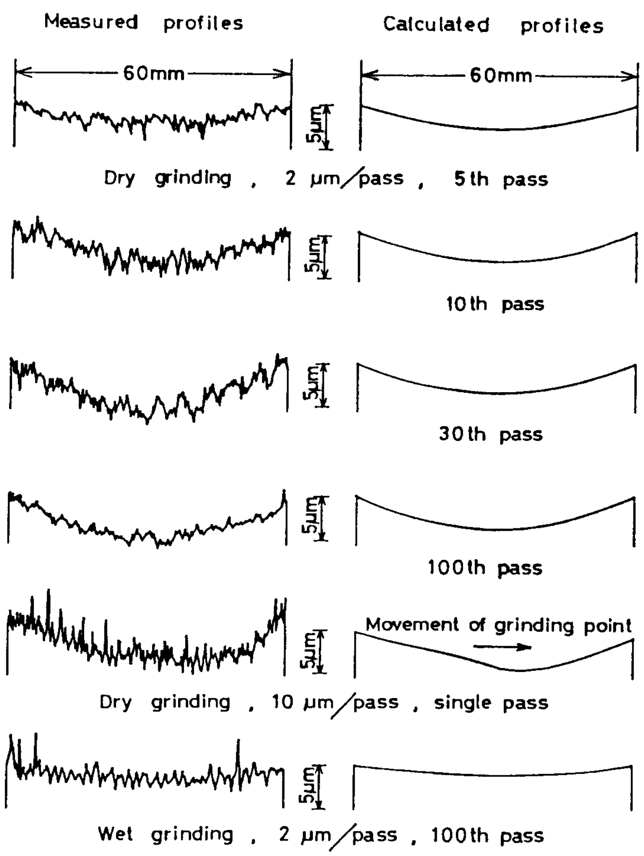

Fig. 23. Profile of workpiece finished by surface grinding[14].

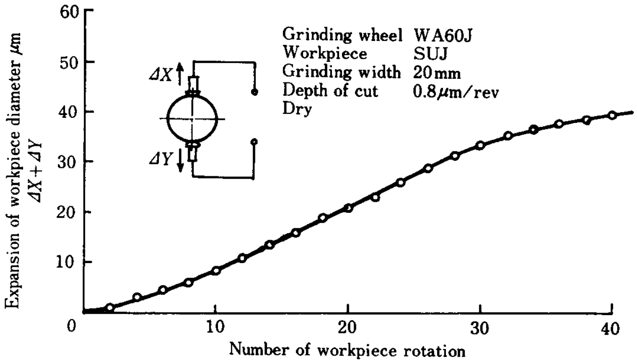

Fig. 24. Expansion of workpiece diameter during cylindrical plunge grinding[15].

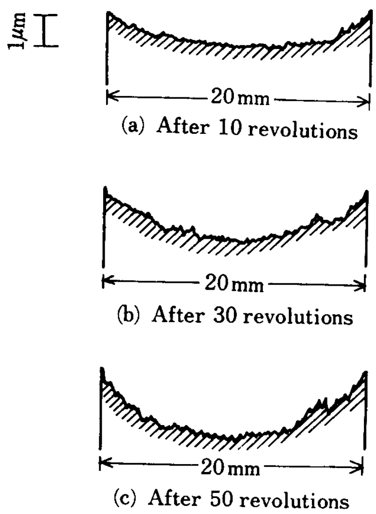

Fig. 25. Cylindricity of workpiece after cylindrical plunge grinding[15].

be represented by the following Fourier's equation,

$$\frac{\partial\theta}{\partial t}=a\left(\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2}\right) \qquad (19)$$

where θ is the temperature rise, x, y, z are the Cartesian co-ordinates, t is time and a is the diffusivity of heat.

Figure 20 shows calculated temperature distribution of a workpiece during surface grinding[14]. It is seen that the temperature rises suddenly when the grinding wheel comes to the grinding point and, after that, drops slowly saw-toothwise near the surface to be ground. Such saw-tooth shaped temperature variation is repeated and mean temperature rises exponentially. The tempera-

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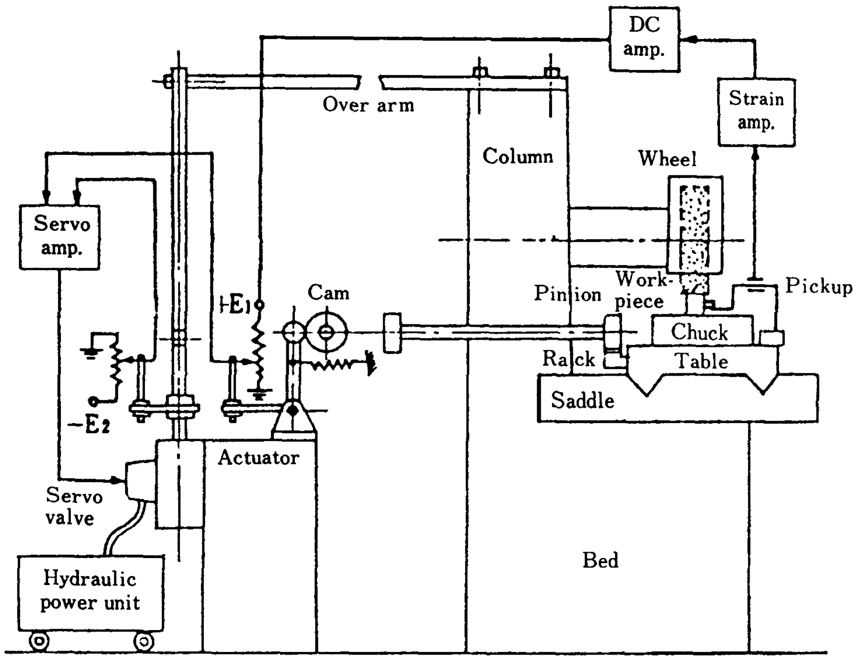

Fig. 26. Surface grinding technique for elimination of workpiece[16].

ture and its variation decrease with the distance from the ground surface. At the bottom reference surface, temperature is almost uniformly distributed. Such temperature distribution will produce the deformation of the workpiece.

Figure 21 is a block diagram showing a grinding system in which actual depth of cut varies because of thermal deformation of a workpiece. Such thermal deformation of the workpiece can be calculated theoretically by following the procedure of a flow chart shown in Fig. 22.

Some examples of the finished workpiece profiles are shown in Fig. 23. It is seen that the calculated profiles coincides well with the measured ones. It should be noted that in surface grinding, workpieces are always formed concavewise like these.

Thermal deformation of a workpiece occurs also in cylindrical grinding. Figure 24 shows that a diameter of a workpiece near the surface being ground expands with progress of grinding process. Figure 25 shows the cylindricity of a workpiece after grinding. It is seen that, since increase of a diameter of a workpiece during grinding is larger in the middle portion than in both ends, the workpiece profile becomes concave after cooling like those in surface grinding[15].

It is possible to eliminate machining errors due to thermal deformation of a workpiece by actively utilizing elastic deformation of a grinding system.

Figure 26 shows a device for automatically eliminating profile errors of a workpiece due to its thermal deformation[16]. The convexwise thermal deformation of the workpiece is detected during grinding by means of a precision displacement pickup. The detected deformation is fed to a servo amplifier as an input signal.

A hydraulic actuator is driven by this signal through an electrohydraulic servomechanism. The displacement of the actuator makes the grinding machine deform elastically by means of a connecting rod and an over arm. Consequently, the relative position of the grinding wheel with respect to the workpiece varies in accordance with detected thermal deformation of the workpiece so as to eliminate the profile error. Some

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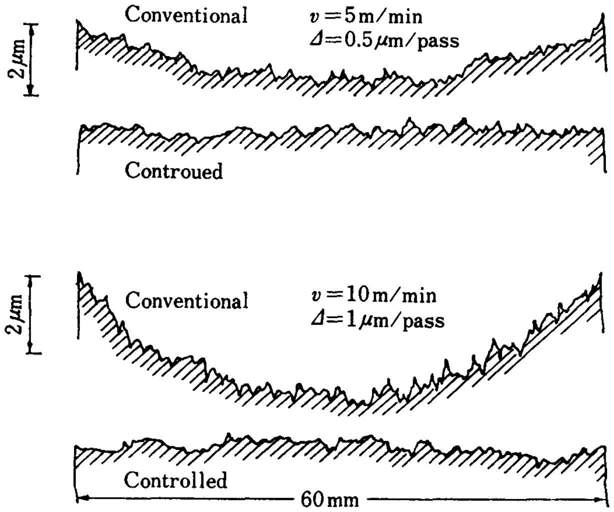

Fig. 27. Effect of controlled surface grinding[16].

examples of the workpiece profiles finished by an ordinary grinding method and the new technique are shown in Fig. 27.

It is seen that in the case of ordinary grinding method, concave profile errors are about 3 μm, however, in the case of new techniqe, the profile errors decrease within 1 μm regardless of grinding conditions[16].

In order to eliminate machining errors due to grinding heat, it is, of course, effective to remove a source of the grinding heat. However, it is generally difficult to control non-steady thermal deformation by using thermal means because of time lag. In such a case, it is effective to control thermal deformation of a workpiece by actively utilizing elastic deformation of a grinding system.

5. Conclusions

This article deals with some problems concerned with geometric accuracies of workpieces in grinding. The obtained conclusions are summarized as follows:

(1) Interaction of dynamic and thermal behaviour among a workpiece, a grinding machine and grinding force plays an important role in formation of geometric errors of a workpiece.

(2) Normal grinding force produces comparatively large elastic deformation of a grinding machine and other parts, and causes large size and form errors of the finished workpiece.

(3) Grinding heat produces comparatively large thermal deformation of a workpiece and causes large size and form errors of the finished workpiece.

(4) It is possible to eliminate the geometric errors produced in grinding by actively utilizing elastic deformation of the grinding system.

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