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Magnetic Fluid Grinding

Introduction

In traditional mechanical surface finishing operations, such as grinding, lapping, honing, polishing, or buffing a shaped solid tool such as a grinding wheel, a lapping plate or a hone is used. These solid tools are pressed mechanically by a screw, oil pressure or spring against the workpiece. However, when grinding advanced ceramics which are brittle, these processes introduce surface defects such as cracks which can significantly reduce the strength and reliability of the parts in service. Also expensive diamond abrasives and long polishing times add significantly to the cost of manufacture. To overcome these problems and against these traditional finishing methods, magnetic field assisted finishing process was developed.

This new finishing method can be classified to two types. The first one is magnetic abrasive finishing which uses a brush of magnetic abrasives for finishing [12]. The polishing characteristics of the magnetic abrasive brush can be altered by varying the magnetic field. The second type, termed, magnetic fluid grinding uses magnetic fluid which is a colloidal suspension of sub domain magnetic particles in a liquid carrier [13]. Magnetic fluid grinding can also be expected to produce salient finishing properties of advanced ceramics by optimum combination of magnetic fluid abrasive grains, and magnetic field. Application of magnetic fluid to surface finishing has been investigated originally by lmanaka el al. [14], followed by Tani et al. [2]. They used magnetic buoyant force of abrasive grains in a magnetic fluid as the grinding force. However, the magnetic buoyant force of abrasive grains was too low to give effective removal rate, and shape accuracy was poorly controlled. To overcome these problems, a special element named 'float' was introduced by Umehara and Kato [15] lo increase the grinding force and improve the shape accuracy. As a result, the combination of magnetic fluid, a float, abrasive grains, and magnetic field showed to form a new practical grinding method named 'Magnetic Fluid Grinding'. This magnetic fluid grinding has been shown to be effective in grinding of ceramic balls [15], a metal cylinder end, a ceramic cylinder, ceramic rollers [16], ceramic plates[17] and a metal pipe.

In following sections Magnetic Fluid Grinding is discussed in detail with respect to operating principle, parameters affecting the process and application.

Working Principle

The starting point of the development of the magnetic fluid grinding process is the theory of ferrohydrodynamics developed by Rosensweig [18]. According to this theory, a buoyant force $F_b$acts on a non-magnetic immersed in a magnetic fluid and subjected to a magnetic field as shown in Fig.1.

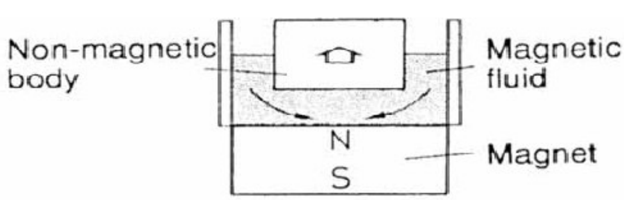

Fig.1 Buoyant force acting on the non magnetic body in magnetic fluid with magnetic field [Umehara et al, 1994]

According to this principle, non-magnetic abrasive grains can be dispersed at a certain position in a magnetic fluid under specially designed magnetic field. Figure 2 shows an example where abrasive grains are floated at a certain height.

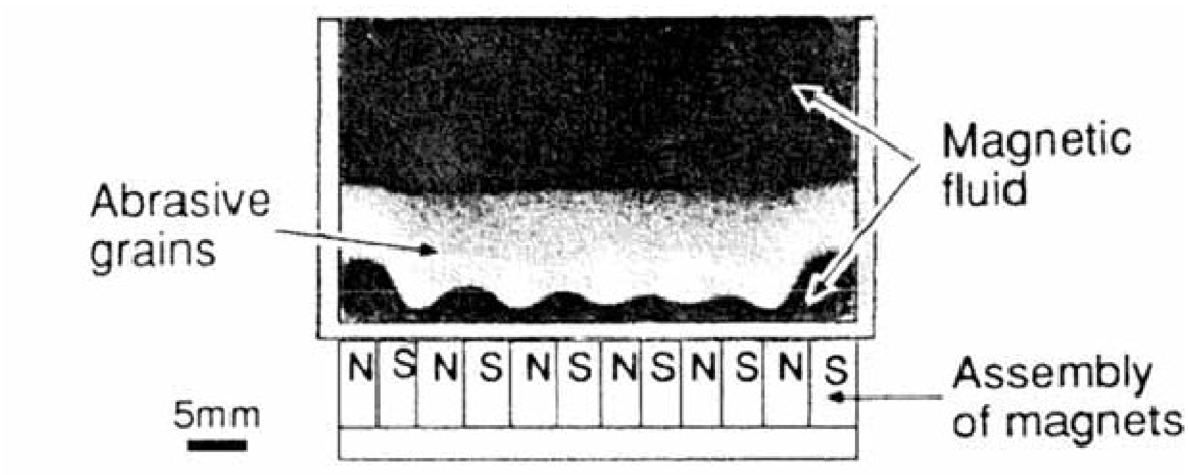

Fig. 2 Floating of abrasive grains in the magnetic fluid under the action of magnetic field [Umehara et al, 1994]

Magnetic fluids used are colloidal dispersions of subdomain ferromagnetic (10-15nm) in various kinds of carrier liquids. One particular class of ferrofluids is made of a stable against particle agglomeration by the addition of a surface active agent. When magnetic fluid is placed in magnetic field gradient, it is attracted towards the higher magnetic field side. If a nonmagnetic substance is immersed in magnetic fluid, it is discharged relatively to lower field side as shown in Fig 3. When the field gradient is set in the gravitational direction, the material is made to float on fluid surface by the action of magnetic levitational force.

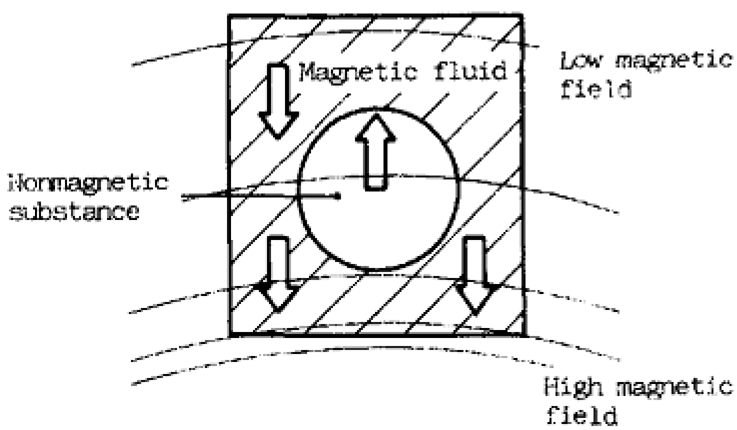

Fig. 3 Mechanism of magnetic buoyant levitation [Tani et al, 1984]

The polishing process in mechanical fluid grinding makes an application of the magnetic buoyant levitational force. Fig 4 shows the principle of ths method. Three pieces of permanent magnets, each having a pole of different direction from the others, cause an unhomogeneous magnetic field whose contour line over the magnets is winding and has a hollow place over the central magnet [2].When magnetic fluid suspending nonmagnetic abrasives is placed close to the magnets, the abrasives are caused to float on the fluid surface and to gather to the

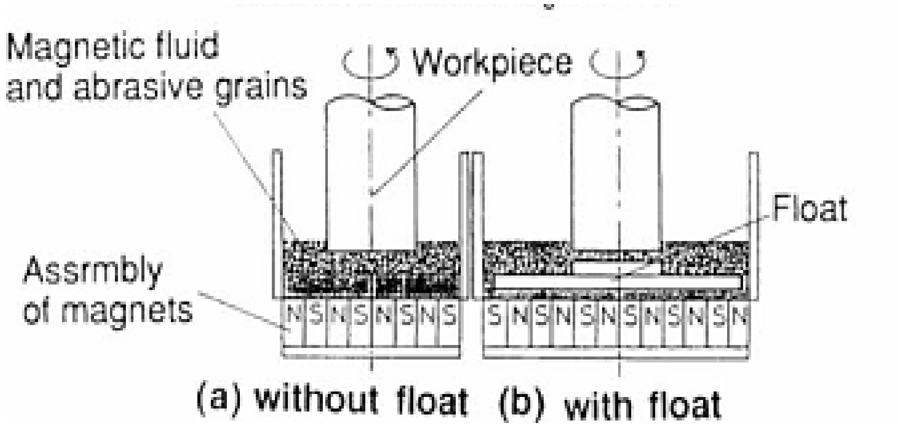

Fig 4 The principle of magnetic fluid grinding with and without a float [Umehara et al, 1994]

above mentioned hollow place. So when the workpiece comes into contact with the compound, the abrasives come into contact with the workpiece surface under the influence of magnetic levitational foce. While the workpiece is revolved in the fluid, the resisitance force against the motion of workpiece is acted to abrasives, because magnetic force prevents abrasives from going over the convexity of magnetic field. As the velocity of the workiece is large, the resistance force increase as the viscosity of the compound increases by higher volumetric contents of the abrasives. Relative motion between the workpiece and the abrasives enables polishing under the influence of levitational force and resistance.

If a workpiece is submerged and rotated in the layer of abrasive grains as shown in Fig.4(a), the surface is ground by free abrasive grains. But the removal rate is found to be very low [2,14] since the total buoyant force of abrasive grains is too small to accomplish large removal rates. If a float is introduced to this system as shown in Fig.4(b), larger grinding pressure can be produced since large buoyant force near the magnet pole surface is transmitted to the grinding surface of a workpiece.

Figure 5 shows an example of grinding pressure P as a function of distance of abrasive grain layer or a float from magnet. Solid lines in this figure show the theoretical values of grinding pressure calculated using the following equation developed by Rosensweig [18],

$$F_b = -\iint_s \left(\mu \frac{Mn^2}{2} + \int_0^{\mu} Mdh \right) n.ds$$

Where F_b is buoyant force of the non magnetic body. 's' area of non magnetic. μ permeability of free space, 'M' magnetization of magnetic fluid, 'Mn' normal component of M to non-magnetic body. 'H' the strength of magnetic field, and 'n' normal unit vector to non-magnetic body. The contact stiffness,which is defined as the grinding load divided by the elastic displacement of the contact surface, in magnetic fluid grinding is smaller than that of the grinding wheei or the polyurethane polisher.Therefore, it is considered that such low contact stiffness in loading with a float can prevent the workpiece surface from severe damage or generation of cracks in finishing of ceramics.

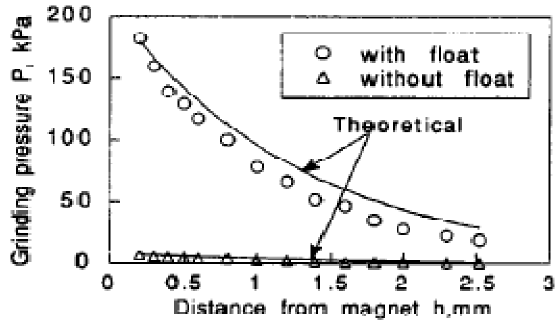

Fig. 5 Grinding pressure P as a function of distances ‘h’ of floating abrasive grain layer and a float from magnet [Umehara et al, 1994]

Figure 6 shows the experimental apparatus of the newly developd polishing process developed by [2]. in order to realize the above-mentioned principle of magnetic buoyant levitation and to evaluate the finishing charecterstics.

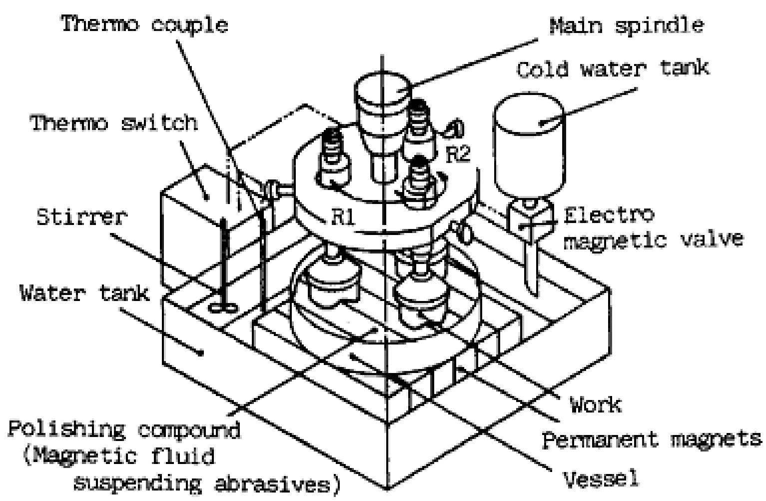

Fig. 6 Outside view of experimental apparatus used by Tani et al.

The apparatus is composed of driving device to rotate the workpiece, several permanent magnets to obtain an unhomogeeous magnetic field and awater tank to control the temperature of the polishing process. The workpiece is fixed to the workpiece attachement through two radial bearings. The revolution of the attachment is given by connecting to the spindle of a vertical milling machine. Therefore the workpiece rotates in opposite direction of the spindle revolution by the friction of polishing surface. The magnets are placed so that the magnetic poles of adjacent magnets are in opposite in order that that the magnetic has a large gradient in both gravitational and lateral direction as well as in order to prevent abrasives from rolling away. As the temperature of the fluid rises, the viscousity of the magnetc fluid lessens and the holding force of abrasives in the lateral direction becomes reduced. Therefore the polishing process is cooled by cold water to prevent the temperature of the compound from rising by polishing.

Literature review

A brief overview of relevant literature reviewed is presented in the following paragraphs:

N.Umehara [1,3,4,6 and 9] developed magnetic fluid grinding for finishing advanced ceramics especially for Si_3N_4 balls. The removal mechanism in this process and the optimum grinding conditions were studied. It was observed high removal rate of magnetic fluid grinding of ceramic balls is a consequence of the large sliding speed between the driving shaft and the balls. A wear coefficient for Si_3N_4 balls of 0.07$\pm$0.02 was observed, indicative of two-body abrasion. A higher removal rate and smaller surface roughness are obtained with Cr_2O_3 abrasives compared with Al_2O_3 abrasives. A new microsurface finishing method of local area using magnetic fluid, abrasive grains and magnet was also proposed. The profile of grinding surface of borosilicate glass is observed as a function of grinding time and magnetic fluid strength. In the case with magnetic field, constant removal rate, a uniform and even smooth surface was obtained. Maximum removal rate of $1.9 \times 10^{-12} m^3$/Nm. Minimum value of maximum surface roughness is 0.1 μm. In the case without magnetic field, removal rate decreases with grinding time, and a large number of irregular and deep scratches remained on ground surface. MFG process was investigated for efficient finishing of plate with a proposed floating polisher. The surface roughness obtained by this method was the same as that by the traditional polishing method. The minimum surface roughness was 0.014 μm Ra. Polyurethane polisher gives a larger removal rate and a smaller surface roughness than unwoven polishers.

Childs [10] developed a model for the mechanics of the process to predict the onset of skidding motions. It considers the force and moment equilibrium of the balls acted on by the forces and moments at the balls contacts with the drive shaft and other surfaces and by fluid drag forces and moments. It presented measurements of the friction coefficients relevant to the process and of the viscosities of magnetic fluids containing grinding grits, for use n the theory. The. model successfully predicts behavior that has been observed in experiments. Skidding is suppressed by high contact loads. Ball motion is sensitive to changes in sliding friction coefficient and fluid viscosity in the range of these variables that occur in practice. Fluid motion modeling, particularly its effect on the viscous drag forces on the balls, is important to understanding the process.

Though extremely effective at providing high performance, polished surface, magnetic float polishing has been used to only finish non-magnetic applications, particularly alumina, zircon, silicon carbide and silicon nitride. This limitation arises from the nature of the magnetic float polishing technique, which is based on the magnetohydrodynamic behavior of the magnetic fluid. Komanduri [11] developed MPF process for finishing magnetic materials. It requires isolating the magnetic workpiece from any appreciable magnetic induction and subsequently polishing he magnetic workpiece utilizing the action of a magnetic buoyancy levitational force with a conventional magnetic float polishing apparatus.

All researchers have unanimously discovered that strength of magnetic field important parameter which decides the amount of stock removal rate and material removal rate in MPF is quite high compare to conventional machining process.

Parameters affecting MFG

Polishing Period. The amount of stock removal increases monotonously with the polishing period, however tends to be saturated as seen from figure 6. This is due to the combined effect that the size of abrasives used does not become optimum to the improved surface roughness with the elapse of time, and also the wet abrasives in magnetic field becomes deprived of the polishing capability by the stirring caused by the revolution of the work.

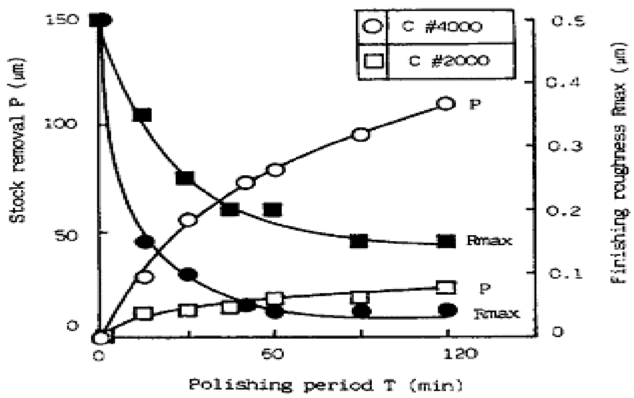

Fig. 6 Stock removal and finishing roughness against polishing period [Tani et al, 1984]

Distance from magnet. Figure 7 shows the finishing charecterstics by polishing position. As the polishing section gets closer to magnets, the levitational force applied to abrasive increases and resultantly the removal rate becomes larger. This phenomenon caused by magneticfield strength is specific to this process. However, when the distance from the magnets is too small, the unhomogenety of magnetic field becomes conspicuous and the removal rate becomes reduced, because magnetic fluid gathers locally in this region. It is evident that the principle of magnetic levitation before mentioned is realized, considering from this effect of magnetic field strength and the observation that the concentration of magnetic field becomes high near the magnets. If the removal rate is high, the finishing roughness reaches the limit determined by the size of abrasives quickly.

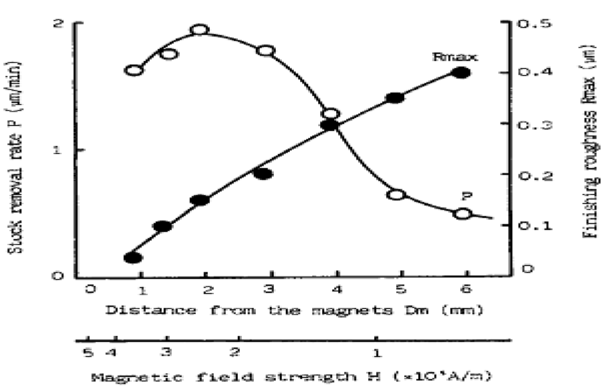

Fig. 7 Effect of polishing position on removal rate and finishing roughness [Tani et al, 1984]

Abrasive concentration. Figure 8 Shoes the effect, of concentration ratio Va of abrasives in magnetic fluid (Va = Volume of abrayives / Sum of volume of abrasives and magnetic fluid) on finishing characteristics. When the ratio is low, the viscosity of the ccmpound is reduced, and when the ratio is high, the reaction of the compotnd by magnetic field proceeds more slowly (the magnetization of the canpound is reduced). On the other hand smother surface finish is attained by higher concentration. Clayey membrane is generated on the surface of mgnetic fluid by the increase of viscosity of the compound. The roughness is affected considerably by the hardness of the layer. thus the finishirg,roughness is nearly constant in the region of the concentration of more than 40vol%.

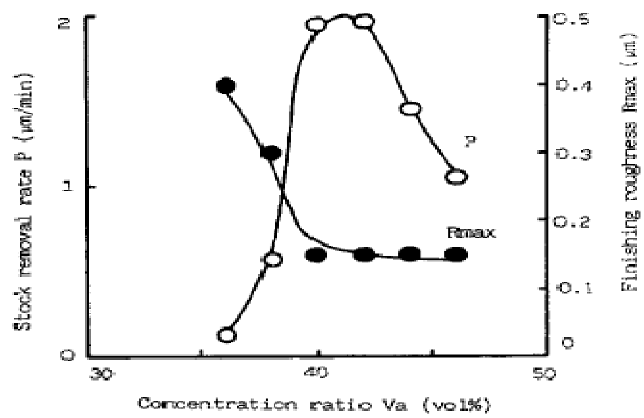

Fig. 8 Effect of concentration ratio of abrasives on removal rate and finishing roughness [Tani et al, 1984]

Grain size. The finishing characteristics are influenced by the scatter of the diameter of abrasive powders because the magnetic levitational force increases in proportion to the grain volume . If finer abrasives are used, the viscosity of the compound is improved and the number of abrasives that talke part in polishing process increases. So both higher removal rate and smoother surface finish are obtained as evident from figure 9. These phenomena are different from those of usual polishing methcd and are characteristic of this method.

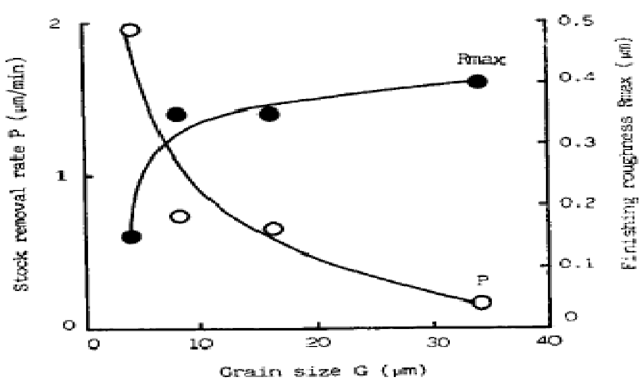

Fig. 9 Effect of grain size on removal rate and finishing roughness.

Chemical composition of magnetic fluid and abrasives. Table 1 shows the chemical composition of typically used abrasives and Table 2 the physical characteristics of magnetic fluid.

Table 1

	SiC	C	Fe	SiO_2
No.1	41.84	1.02	0.38	42.50
No.2	93.98	0.28	0.26	2.41
	Al_2O_3	Na_2O	Fe_2O_3	SiO_2
No.3	99.6	0.2	0.03	0.02

(unit:weight%)

Table 2

	Carrier liquid	Viscosity (mPa·s) at 25°C	Specific gravity at 20°C	Saturation magnetization (mT)
LS-40	Eicosyl naphthalene	32.0	1.345	30.5
SP-40	Spindle oil	33.0	1.275	26.4
W-40	Water	4.5	1.424	31.0

The removal rate is maximum when the carrier liquid of magnetic fluid is eicosyl naphtnalene (mgnetic fluid is raved as LS-40) and the abrasives are C grain (No.1) that contains 42.5weight% $Si0_2$. The viscosity and saturation magnetisation of LS-40 is very high and these abrasives have negative affinity for LS-40. The removal rate of A grain (No.3) is next and that of C grrain (No.2),whose composition of SiC is more than 90weight% is minimum for LS-40. As abrasiveshave great affinity for water in general , the removal rate of W-40 in water solvent is minimum. These results of W-40 is completely contrary for kinds of abrasives to that of LS-40, so it can be said that abrasives with high affinity for water is desireable for the polishing when LS-40 is used [2]. Thus it can be said that an affinity between abrasives and magnetic fluid affects the removal rate enerally in this process.

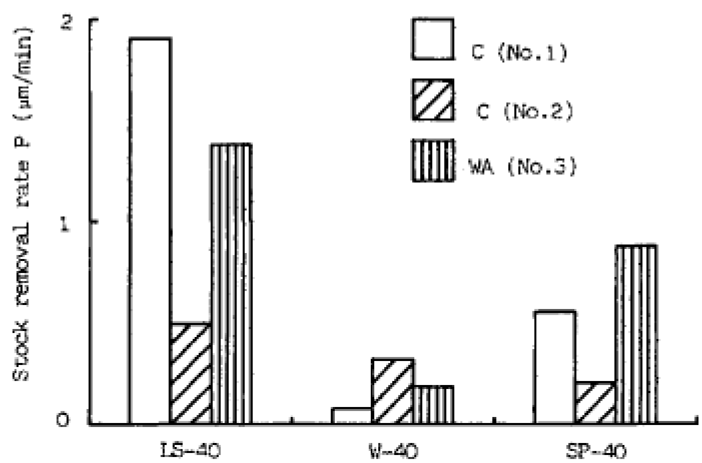

Fig. 10 Effect of affinity between abrasives and magnetic fluid on removal rate [Tani et al, 1984]

Application of Magnetic fluid grinding

Silicon nitride balls: Figure 11 shows a schematic diagram of the grinding apparatus for finishing ceramic balls used for ceramic ball bearing a plication [15] .Magnetic fluid, float, abrasive rains, as-sintered ceramic galls, and permanent magnets are arranged as shown in Fig.11. A float, abrasive grains, and ceramic balls which are all non-magnetic materials are floated in the magnetic fluid by magnetic buoyant force. Balls are rotated and revolved along the inner wall of the guide ring by the driving shaft, they are ground by the abrasive grains in the magnetic fluid. The removal rate of tte silicon nitride balls (made by pressureless sintering) increases with the grinding load and the rotational speed of the driving shaft. Maximum removal rate of silicon nitride balls was 12.4 μm/min with SiC abrasive grains. This removal rate is about 40 times larger than that by traditional V-groove lapping method. Surface roughness decreased with the decrease in the mean grain size of the abrasive grains. Minimum surface roughness was 0.1 μm Rmax

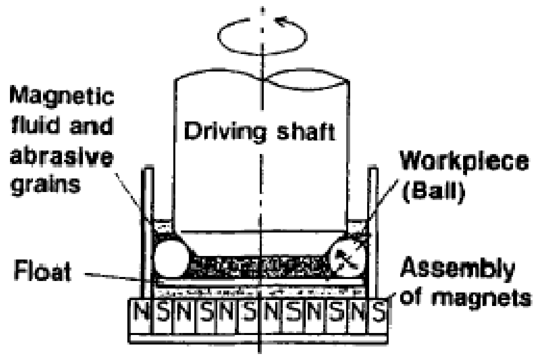

Fig. 11 Schematic diagram of the magnetic fluid grinding apparatus for finishing advanced ceramic balls [Umehara et al, 1990]

Silicon nitride rollers: Figure 12 is a schematic diagram of the grinding apparatus for finishing ceramic rollers [16].These rollers are as-sintered silicon nitride made under hot isostatic pressure. The rollers are pressed against a driving shaft by a cylindrical float which is pushed by the magnetic buoyant force. As the rollers are rotated by the driving shaft, they are ground by abrasive grains in the magnetic fluid. The revolution of the rollers is prevented by a roller holder. because of its flexible support with a float. The cylindricity and circularity of the as-sintered silicon nitride rollers were reduced to one tenth of their initial values within three hours. Maximum removal rate was 0.76μm/min. Minimum cylindricity was 22 μm. Minimum circularity was 3.18μm around the center of the roller. The removal rate was found to be increased with the grinding load and the rotational speed. Cylindricity showed a minimum value at a certain grinding time.

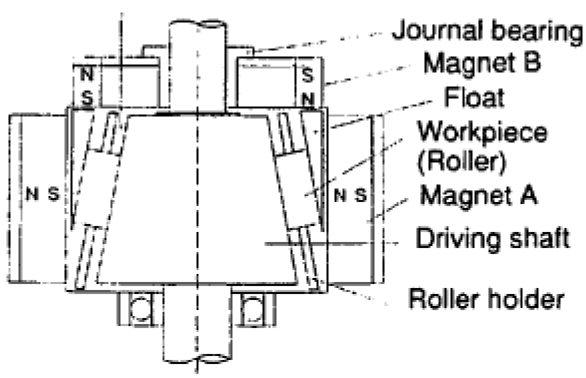

Fig. 12 Schematic diagram of the magnetic fluid grinding apparatus for finishing advanced ceramic rollers [Umehara et al, 1992]

Alumina plates: Figure 13 is a schematic dia ram of the grinding apparatus for finishing ceramic plates (25.4 mm width and 5mm thickness) [17]. The plates are aluminium oxide made by pressureless sintering and are bonded on three planetary disks which are rotated at the same rotational speed as the sun disk but in opposite direction for obtaining uniform sliding distance on the alumina plates. The float has a step as shown in Fig. 14. Optimum step width of the float provides minimum flatness. A minimum flatness of 0.5 μm is obtained in the case of the float with a 18mm step width. The flatness is thus a function of the step width of the float. Optimum grinding load and abrasive grain size exist for the removal rate and flatness. Observed values of maximum removal rate, minimum flatness, and minimum surface roughness were 6.4μm/min, 0.5 μm and 0.06 μmRa , respectively.

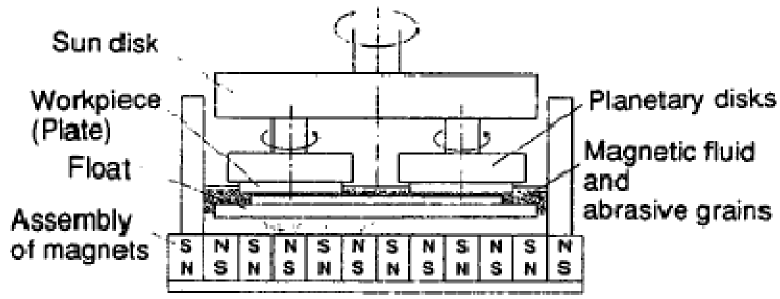

Fig. 13 Schematic diagram of the magnetic fluid grinding apparatus for finishing advanced ceramic plates [Umehara et al, 1992]

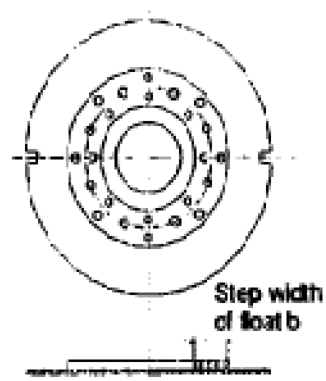

Fig. 14 A float with a Step [Umehara et al, 1992]

Conclusions

Recentely, finer finishing of geometrical accuracy such as surface roughness and flatness has became required with certain electronics and optics components in order to attain higher performances. At the same time, lessening the thickness of polishing affected layer where impurties such as abrasives or stresses remain is similarly considered important, since such has bad effects on the mechanical charecterstics of components such as fatigue strength and the corrosive resistance. Various types of process were developed in this respect. Pressure applied in these processes was reduced to achieve nanao finish however Material removal rate was found to be very low

In this regard magnetic fluid grinding is a superior method. Both higher removal rate and smother surface finish in this polishing metod was attained by stronger magnetic field and finer abrasuives. The removal rate of this method is about three times larger than that of traditional polishing. Surface roughness value upto 0.014μm Ra has been achieved [6]. The characterstics of this method are summarized as follows:

1. Many abrasives participate in polishing at finishing surface due to the application of magnetic levitational force
2. The polishing pressure of each grain is small because abrasives are floating in the magnetic fluid
3. The temperature rise at the polishing point is supressed since the magnetic fluid has large thermal conductivity
4. Higher flatness of the finished surface can be obtained by holding the workpiece closer to magnets and applying higher magnetic levitational force to the abrasives.
5. Viberation and impact that are produced between the workpeice and the tool at high grinding speeds is reduced by the float which is flexibly supported by the magnetic fluid. So the system can operate at high speeds (more than 10,000 rpm) for accomplishong high removal rates.
6. MFG can be applied to a variety of geometry (balls,rollers and flat surfaces) and work materials (alumina and silicon nitride).

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