Study on the Chucking Force of an Electro-Magnetic Chuck*

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The clamping condition of a workpiece and/or a tool has a considerable effect on the machining efficiency and machining accuracy. It is, therefore, necessary to examine the clamping characteristics of chucks and fixtures. This paper describes the clamping characteristics of an electro-magnetic chuck which is one of the most commonly used clamping attachments in a surface grinder. The distribution of magnetic flux density and the normal and the tangential component of the chucking force were measured using the gauss meter and the strain gauge type load cell. From the measured results, the following conclusions can be drawn;

- 1) The distribution of magnetic flux density is not uniform, being variable with the perpendicular position to the separator.
- 2) The chucking force is not always in proportion to the contact area and the relative position between the workpiece and the magnetic poles has a remarkable effect on it.
- 3) The clamping characteristics are significantly influenced by the contact conditions such as the surface roughness and the flatness of a workpiece.

Key Words: Electro-Magnetic Chuck, Chucking Force, Clamping Characteristics, Magnetic Flux Density.

1. Introduction

In machining process, the condition to clamp a workpiece or to set a tool is closely related to the cutting phenomena and the chatter vibrations. In addition, as is generally known, it delicately affects the machining limit, machining efficiency and machining accuracy⁽¹⁾. In order to clarify the cutting mechanism and the deformation behavior of a workpiece, it is necessary to examine the clamping condition of chucks and fixtures, which is an important boundary condition. From this point of view, some research works have been carried out with respect to three-jaw-chuck⁽²⁾, taper connection⁽³⁾ and center⁽⁴⁾.

As for the method to clamp a workpiece, various types and configurations have been put into practical use corresponding to the kinds of machine tools and the shapes of workpieces. The electro-magnetic chuck has been widely used in a surface grinder, because of its easiness of operation and possibilities to get high

flatness and parallelism without difficulties. Not only excellent machining accuracy but also high reliability and safety are required in grinding process, because there is a danger of a grinding wheel being broken down due to its high rotational speed. Considering these situations, to make clear the clamping characteristics of an electro-magnetic chuck is deemed one of the urgent needs. Although the technologies to utilize the electro-magnetic power have been developed and spread in many fields, there are few studies on the electro-magnetic chuck from an engineering viewpoint⁽⁵⁾.

For example, there are a number of ambiguous points regarding the chucking force of an electro-magnetic chuck, i.e., force to clamp a workpiece, and the influencing factors. Therefore, some serious problems still remain in the actual grinding process as follows;

- (1) The relationship between the configuration of a workpiece and the chucking force of an electro-magnetic chuck (the dimensions and shape of a workpiece which can be clamped).
- (2) The machining limit due to the chucking conditions (required chucking force in grinding operations).
- (3) The effects of clamping conditions on the machining accuracy (problem related to the bending deformation of a thin workpiece).

The clear countermeasures for these problems have not been established so far. In spite of the already existing techniques for its application, the basic research on the clamping characteristics of electro-magnetic chucks has been neglected.

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Therefore, an experimental investigation as follows was carried out with aim at clarifying the clamping performance of an electro-magnetic chuck. Choosing the rectangular electro-magnetic chuck as a research object, the distribution of magnetic flux density over its surface and both of its normal and tangential chucking force were measured by using the gauss meter and the strain gauge type load cell respectively. From the results, the correlation between the magnetic flux density and the chucking force was made clear, and furthermore the fundamental clamping characteristics of an electro-magnetic chuck were discussed examining the effects of the dimensions and contact conditions of a workpiece on the chucking force.

2. Experimental apparatus and techniques

In this study, the experiments were performed using the rectangular electro-magnetic chuck as shown in Fig.1 which is widely used as a clamping attachment to a surface grinder. The rated voltage and the watt consumption of this chuck are 80 V and 24 W respectively. For the convenience of explanations, the magnetic poles are distinguished between the magnetic pole A and the magnetic pole B as shown in Fig.1. X, Y and Z axes are fixed in perpendicular, parallel to the direction of the separator and vertical to the face plate surface respectively, and the measured results were rearranged on this rectangular co-ordinate system.

In order to make clear the electro-magnetic characteristics of the chuck, the distributions of magnetic flux density over the face plate surface were measured by the gauss meter. In this measurement three-dimensional distributions were examined moving the probe with the element, which is based on the Hall Effect, in three directions over the chuck surface. The element used here is 0.15 mm in thickness; 1.2 mm in width and 2.5 mm in length. As the gauss meter indicates only the normal component to the element, the scalar quantity and the direction of the vector of the magnetic flux density were

- 1: Main Body
- 2: Face Plate
- 3: Separator
- 4: Magnetic Pole A
- 5: Magnetic Pole B

Fig.1. Electro-magnetic Chuck

obtained from the calculation for the composition of both normal and tangential components which were measured by the probes installed in perpendicular and parallel to the face plate surface.

The measurements of the chucking force were performed in accordance with the test procedure specified by JIS 'Electro-Magnetic Chuck' (B6156). Fig.2 shows a schematic diagram of the measuring apparatus for chucking force. As shown in Fig.2(a), the testpiece clamped on the surface of an electro-magnetic chuck connects with the piston of a hydraulic cylinder by the attachments and the wire rope. The testpiece is subjected to an upward loading by the hydraulic power and a tension at the moment when the testpiece is pulled apart from the chuck is determined as a normal component of chucking force F_n which is measured by the strain gauge bonded onto the attachment.

For the measurement of a tangential component of chucking force, the experimental apparatus for a normal one was moved to the horizontal place as shown in Fig.2(b) and was used in the same manner as mentioned above. In this case the tangential chucking force F_t is considered the tension at the moment of the testpiece being shifted, which is detected by the non-contact type displacement pick-up. To avoid the undesirable effect of the electromagnetic force on the measured results, we used the brass as a non-magnetic material for attachments and an anti-magnetic type strain gauge for force measurements.

- 1: Hydraulic Cylinder
- 2: Piston
- 3: Attachment
- 4: Strain Gauge
- 5: Wire Rope
- 6: Testpiece
- 7: Electro-Magnetic Chuck
- 8: Saddle
- 9: Guideway
- 10: Support

(a) Normal Chucking Force

(b) Tangential Chucking Force

Fig.2. Schematic diagram of measuring apparatus for chucking force

As a preparatory experiment to check the performance of this measuring system, a test was conducted using a testpiece and a spring balancer specified in JIS. From the test results, it is confirmed that the electro-magnetic chuck examined satisfies the specifications of JIS. Moreover, it is found that by this system the chucking force can be measured more accurately than by the method using the spring balancer. Material of testpiece is SS41 (Rolled Steel for General Structure) and surface roughness of it and of the chuck are 0.12 μm each unless otherwise specified.

3. Measured results and discussions

3.1 Magnetic flux density

First of all, the magnetic flux density over the chuck surface was examined. The distributions of normal and tangential components in X-Z plane perpendicular to the separator are shown in Fig.3. In this case, the poles A and B are magnetized N (north pole) and S (south pole) respectively under the condition that the electric current I supplied to the chuck is 0.18 A. This figure indicates only a typical result in the region of $-7 < X < 21$ mm, but the density actually distributes smoothly over the whole of the chuck surface. According to the measurements over a wide range, the distribution patterns for one span of 28 mm will be the same in the central area except near the edge of the chuck. This span exactly agrees with the pitch of each pole. On the other hand, the magnetic flux density in Y-Z plane will be quite constant in the Y direction in the central region. From these results, it can be said that in the case of a rectangular electro-magnetic chuck the distribution of magnetic flux density is considered two-dimensional in X-Z plane.

As can be seen from Fig.3, in both cases of normal and tangential components, the absolute value of the magnetic flux density, $|B_0|$, decreases with an increase of the distance from the chuck surface, Z . Regarding the tangential component, $|B_0|$ becomes almost zero at the position of $Z > 15$ mm. On the contrary, regarding the normal one, in the area where $Z < 30$ mm $|B_0|$ does not come close to zero and indicates a positive value over the whole region. Moreover, the distribution near the chuck surface is very complicated with six peaks in the span comparing with that of tangential one. When changing the flow direction of the electric current I for the chuck is changed, the poles A and B are oppositely magnetized but the absolute value $|B_0|$ shows quite the same tendency. In other words, the distribution can be obtained by transforming the result shown in Fig.3 as it is symmetric with respect to the horizontal axis. Consequently, the absolute value of normal component at the pole A is always larger than that at the pole B regardless of its polarity.

Fig.4 shows the scalar quantity and the direction of the vector of the magnetic flux density in X-Z plane by using arrows. In this case, the electric current I is 0.24 A and the poles A and B are magnetized S and N respectively, which is contrary to the situation shown in Fig.3. The vectors near the chuck surface indicate the direction from N pole to S pole, but in the region where $Z > 15$ mm all vectors face the chuck surface at a right angle. In addition, the scalar quantity near the pole A is larger than that near the pole B, which is similar to the relationship obtained from Fig.3. Thus, it is obvious that the magnetic flux density over the chuck surface is not distributed uniformly and that a remarkable difference in the electro-magnetic behaviors is recognized between the poles A and B.

(a) Normal Component

(b) Tangential Component

Fig.3. Normal and tangential component of magnetic flux density

The relationship between the magnetic flux density and the electric current I for chuck is shown in Fig.5. The absolute value $|B_0|$ of tangential component increases with an increase of I and it becomes nearly saturated with the rate of increase falling in the region of $I > 0.2$ A. In the case of normal component, the same relation is observed at the pole A ($X=0$), but at the pole B ($X=14$) $|B_0|$ dose conversely decrease where $I > 0.2$ A. From these results it is evident that the characteristics in regard to the electric current are also clearly different between the poles A and B. According to the electro-magnetics, with an increase of the current for coil the magnetic flux density will proportionally increase and will be saturated to a specific value of the magnetic material (6). This saturated phenomenon may appear in the result shown in Fig.5.

Synthesizing the results mentioned above, it can be said that the magnetic flux density over the chuck surface is not uniform but repeatedly distributed with the span which is consistent with the pitch of the poles and separator. In addition, a large difference in electro-magnetic properties is obviously recognized between the poles A and B. These characteristics may depend on a particular structure of an electro-magnetic chuck which is designed for the purpose of the enlargement of the chucking force. Namely, divided by the separators, the face plate is composed of many magnetic poles whose polarities N and S are alternate and there are a coil and a core inside of the chuck. The portion of the pole A is directly connected with the core and on the contrary the pole B is isolated from the core with a certain gap. Due to the structural characteristics of a chuck, it is considered that the polarity of the pole A affects definitely the distribution of magnetic flux density over a wide area. Furthermore, the different behaviors with respect to the electric current between the poles A and B may be also explained well in the same way.

Fig.4. Distribution of magnetic flux density over chuck surface

As is known, the magnetic flux density is in close connection with the chucking force mentioned later by the following equations (6), (7):

$$B = B_0 \cdot (1 + \chi) \quad (T) \text{-----}(1)$$

$$F_n = (B^2 / 2 \cdot \mu_0) \cdot S \quad (N) \text{-----}(2)$$

where, B : magnetic flux density produced in the magnetic material (T)

B_0 : magnetic flux density produced in space (T)

χ : relative susceptibility of the magnetic material

F_n : normal component of chucking force (N)

μ_0 : magnetic permeability of vacuum (H/m)

S : contact area (m^2)

When the testpiece as a magnetic material is clamped by the electro-magnetic chuck, a magnetic flux density is produced in the testpiece according to Equ.(1). If B is perpendicular to the contact surface and is distributed uniformly, the normal component of chucking force F_n can be expressed by using B as shown in Equ.(2).

In this way, there exists an obvious relationship between B_0 and F_n . However, a number of problems have been left unsolved from a practical point of view, because B_0 makes a complicated behavior as mentioned above and the basic data are not sufficient concerning the effect of the contact conditions on B . In consequence, it is very significant in engineering fields to examine the factors affecting the chucking force considering the distributed conditions of magnetic flux density.

Fig.5. Electric current for chuck and magnetic flux density

3.2 Chucking force

3.2.1 Normal and tangential component of chucking force

With special attention to the distribution of magnetic flux density which remarkably changes with the location in X direction, the chucking force was measured varying the chucking position in X direction. The dimensions of a testpiece are expressed by the symbols L_x , L_y and L_z as shown in Fig.6. The origin O is fixed at the center of the pole A and the chucking position X_c is determined by the distance between the origin and the center of a testpiece. Through the measurements of the chucking force it is also confirmed that the force changes at regular intervals which are in good correspondence with the spans of the poles similarly to the magnetic flux density. For this reason, only the results in the range of $0 < X_c < 28$ mm will be explained and discussed below.

Fig.7 shows the normal and the tangential component of the chucking force, F_n and F_t , at each chucking position X_c with the variation of the testpiece length L_x . Both F_n and F_t considerably vary depending on the chucking position X_c . Moreover, the chucking position where the chucking force takes a peak value is apparently different due to the testpiece length L_x . In the case of Fig.7, there is one couple of maximum and minimum peak values within one span. According to another experiment, two couples of them are observed in some cases, which will be shown in Fig.13. From these results, it is clear that both the testpiece length L_x and the chucking position X_c have a noteworthy effect on the chucking force and that the number of poles and the condition at the contact area are significant factors to examine the chucking force.

Fig.6. Testpiece and chucking position

Comparing the normal component F_n with the tangential one F_t , the peaks appear at the same chucking positions and their behaviors are similar to each other with respect to X_c . The coefficient of friction μ ($=F_t/F_n$) becomes about 0.1-0.2 which is smaller than the coefficient of friction in metal to metal contact, and this implies the weakness of the tangential component of the chucking force F_t . Meanwhile, the reason why the experimental values of the coefficient of friction are so widely scattered may be found in the following; the amount of scatter in measurements of F_n and F_t reaches about 10% and the contact conditions delicately affect the chucking force. Bearing this fact in mind, we may consider the relationship between F_n and F_t to be almost constant as a coefficient of friction.

(a) Normal Chucking Force

(b) Tangential Chucking Force

Fig.7. Normal and tangential component of chucking force

3.2.2. Effects of dimensions of workpiece

As mentioned above, the length of a testpiece L_x is one of the important factors affecting the chucking force. Subsequently, the effects of the width L_y and height L_z were examined in the same manner. Henceforth the results concerning F_n will be explained, since F_t is easily expected from F_n by taking the coefficient of friction into consideration.

Fig.8 shows the result when the width of a testpiece L_y is varied. F_n remarkably changes depending on X_c but the difference between the maximum and the minimum peak values decreases as L_y increases. In addition, the position where F_n shows a peak value does not change independently of L_y . These results disagree with the results obtained with the variation of L_x as shown in Fig.7. It is evident that the effect of L_y is quite distinct from that of L_x .

Therefore, the result rearranged by the contact area S is shown in Fig.9. In this figure, the solid and the broken lines indicate respectively the mean value of F_n at each chucking position and the difference between the maximum and the minimum peak value. With the variation of the length L_x , both F_n and its difference remarkably increase in proportion to the contact area S . On the contrary, with the variation of the width L_y , F_n is nearly constant and its difference reversely decreases as S increases. From these results, it can be said that the chucking force is not necessarily connected with the contact area and that the contact length in the direction perpendicular to the poles and separator plays an important role in regard to the chucking force. The difference of the effect on chucking force between L_x and L_y is due to the phenomenon of the concentration of the magnetic flux density in a workpiece. In other words, the number of poles and the polarities in contact area remain unchanged essentially even when varying the width L_y . Thus, L_y has a slight influence on the chucking force because L_y is scarcely related to the concentration of the magnetic flux density.

Fig.8. Effects of testpiece width

The effects of the height L_z and the electric current for chuck I are shown in Fig.10. F_n is almost constant independently of L_z . Summing up the results as regards the dimensions of a testpiece, L_x has the largest effect on the chucking force, and L_z has the smallest one. This relation is derived from the fact that the chucking force is determined by the magnetic flux density in the testpiece near the contact surface. Accordingly, L_z which does not take part in the variation of the contact surface has little influence on the chucking force. However, there still remain some problems unsolved in the application of the result obtained here to the case of a thinner testpiece.

As for the electric current I , F_t steeply increases, settling to a constant value with an increase of I . Same relationship between F_n and I is observed from another experiment and this coincides with the measured results about magnetic flux density as shown in Fig.5. It is said that when I is sufficiently large, the magnetic flux density in a testpiece becomes saturated and then the chucking force also saturates to a constant value.

Fig.9. Chucking force with variation of contact area

Fig.10. Relationship between chucking force and electric current

3.2.3. Effects of contact conditions

Fig.11 shows the effect of the roughness R_a on the chucking force. With an increase of R_a , F_n decreases in proportion to R_a , but F_t decreases showing a slight maximum peak value. The reduction of the chucking force due to the increment of the surface roughness is compared to the effect of the surface roughness on the contact thermal resistance or contact electric resistance. Namely, the explanation might be made as follows; the larger the surface roughness is, the larger the rate of non-contact part becomes; and a large difference of the magnetic permeability between steel and air causes a change in the magnetic flux density; as a result the chucking force drops. On the other hand, the reason why a slight maximum peak value is observed in the case of F_t cannot be clearly given due to an insufficient number of experiments conducted here. There may be a phenomenon that a projected portion of the testpiece surface cuts into the separator surface because the separator is made of brass which is softer than steel. It is, however, necessary to examine the physico-chemical phe-

(a) Normal Chucking Force

(b) Tangential Chucking Force

Fig.11. Effects of surface roughness

nomena in surface and the deformation behavior from a microscopic point of view in order to solve this problem related to the contact phenomena. This is considered to be the subject for a future study.

Meanwhile, the machine parts with a groove as shown in Fig.12 are widely applied in order to achieve high contact pressure and to avoid the difficulties to obtain high accuracy in flatness of contact surface. The effects of the groove depth d and width c on the chucking forces are investigated as shown in Figs.12 and 13. As can be seen from Fig.12, with an increase of d , F_n steeply decreases and saturates to a constant value in the case of $d > 1$ mm. This result yields the following assumption; when d is small it plays an important role just as the surface roughness which has a considerable influence on the chucking forces; but on the contrary when d is large it hardly affects them similarly to the effects of the testpiece height L_z . From this fact it is easily surmised that the flatness which is in correspondence with the groove depth is an important factor to examine the clamping characteristics of electro-magnetic chucks.

Fig.13 shows the results when varying the groove width c . At the chucking position where $X_c = 0$ or 28 mm, F_n and F_t decline as c increases. A noteworthy behavior is observed at another chucking position. For example, at the position of the separator where $X_c = 7$ or 21 mm, F_n and F_t reversely increase with an increase of c , especially this is clear in the case of F_t at the position of $c = 12$ mm. This complicated behavior as regards the groove width is closely related to the effects of both L_x and X_c , which interfere and intensify each other and in this connection the influences of the groove width delicately changes depending on X_c . A detailed investigation on the magnetic flux density in a testpiece is significant to provide a clear explanation for this complicated behavior.

Fig.12. Effects of groove depth

(a) Normal Chucking Force

(b) Tangential Chucking Force

Fig.13. Effects of groove width

To summarize the results mentioned above, the factors affecting the chucking forces are roughly classified into two groups as follows:

- (1) Conditions of contact; contact area, surface roughness, flatness.
- (2) Conditions of magnetic flux density; chucking position, electric current for chuck, number of poles in a contact area.

In order to clarify the clamping characteristics of an electro-magnetic chuck, it is necessary to examine these conditions and to investigate their interaction.

4. Conclusions

The magnetic flux density and the chucking force of an electro-magnetic chuck have been investigated to make clear the clamping characteristics which are in close relation to the machining accuracy and machining efficiency. From the measured results obtained here, the following conclusions can be drawn:

- (1) The magnetic flux density over a chuck surface is not distributed uniformly but it changes at regular interval with the perpendicular position to the poles.
- (2) The chucking position which is the relative distance between a testpiece and poles has a remarkable effect on the chucking force.
- (3) The relationship between the normal and the tangential component of the chucking force is approximately expressed by a coefficient of friction.
- (4) The chucking forces are not always in proportion to the contact area and the

length perpendicular to the poles is the most important factor affecting them.

- (5) The chucking force is significantly influenced by the contact conditions such as the surface roughness and the flatness of a workpiece.
- (6) The characteristics mentioned above are considered to be related to the structure of an electro-magnetic chuck.

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