Attractive Fixture System Based on Magnetic Field and Friction Force for Numerically Controlled Machining of Paper Honeycomb Core

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In order to improve the precision of machining and reduce the processing cost of paper honeycomb core, a new method is presented to fix the honeycomb core work piece to the working platform using magnetic and frictional forces. In this method, iron powder is used as a medium instead of the traditional adhesive-based material to achieve the bonding between the work piece and the working platform. Iron powder is poured into honeycomb cells until it reaches the desired height using a numerically controlled iron powder feeder system. In addition, a magnetic working platform is manufactured and placed on top of the station of the milling machine. The magnetic field produced by the magnetic working platform is leaded to the iron powder while the magnetic field control system switches on. More precisely, the mutual magnetic attraction between the iron powders located in different cells of the honeycomb and between the iron powder and the platform is generated. While cutting force is applied to the work piece, two types of friction force occur. One is between the iron powder and the wall of the honeycomb cells, and other one is between the work piece and the working platform. Once the resultant friction force balances the machining load, the work piece will be then fixed to the platform. In this paper, a new bonding system based on the new method is introduced and demonstrated.
[DOI: 10.1115/1.2039944]

1 Introduction

Honeycomb core is usually formed using either metallic sheet or non-metallic materials such as resin-impregnated paper or woven fabric. Shaped into hexagonal nest-like cells, a honeycomb core is very similar to a cross section of a beehive in appearance. There are many valued properties in this structure, such as high strength to weight ratio, corrosion resistance, fire resistance (self-extinguishing feature), and excellent dielectric property. In practice, honeycomb core components are usually sandwich bonded using adhesive between two high-strength thin sheets made of either metal or glass fiber to form a honeycomb sandwich structure. Honeycomb sandwich structure is one of the first composite structures that have been used broadly. Virtually honeycomb sandwich has been used in almost all commercial airplanes, helicopters [1], and space vehicles. In addition, the structure has also been commonly used in cargo containers, movable shelters, the interior of navy ships, small boats, automobiles, residential construction materials, and a great many other daily used items.

Although honeycomb sandwich structure has many advantages over traditional structural materials, its application is still limited because some major issues have not been resolved yet. For instance, the durability of the adhesive bond between the core and the skins needs to be improved, and the structure is very difficult to repair. In addition, because of its characteristic structure, honeycomb core component is very difficult to machine with a high precision. According to our previous studies [2,3], honeycomb sandwich structure is often damaged due to failure of the adhesive bond between the core material and the skins, which is directly related to the precision of the machining process. Because of the poor precision of the machining process, the surface of honeycomb core components cannot match the shape of the skin. As a result, defect exists in the adhesive bond, which reduces the durability and life of the structure dramatically.

In order to obtain a high precision of machining, honeycomb core work piece needs to be fixed reliably to the working platform during the processing.

In this paper, instead of adhesive, a new magnetic and frictional force based bonding method [4] is presented to fix a honeycomb core work piece to a high-speed numerically controlled (NC) milling machining. It is demonstrated that with the new fixture method, the work piece is fixed much more reliably compared with the traditional method. Consequently, higher precision of machining is achieved.

2 Traditional Fixture Methods

Due to special mechanical property and appearance of honeycomb core, its fixture methods for machining process are different from the methods used for common metal materials [5,6].Traditionally, three fixture methods, polyethylene glycol method, adhesive tape method and vacsorb method, are used around the world [7]:

(1) Polyethylene glycol method. Polyethylene glycol material possesses solidify property, which melts at a certain temperature ranging from 70 to 90 °C and solidifies as the temperature comes down. Figure 1 illustrates the principle. In this method, polyethylene glycol is deposited on the working platform in advance. While polyethylene glycol keeps the melted state under the certain temperature, core material is pressured onto the working platform surface and applies pressure load until the polyethylene glycol solidified.

Using this method, vacuum bag and autoclave are necessary to ensure the solidification process of polyethylene glycol. But vacuum bag and autoclave are very expensive. On the other hand, the polyethylene glycol is difficult to clean no matter on the working platform or in the honeycomb core cells. So it is costly and inconvenient.

(2) Adhesive tape method. This method is broadly used in China. In this method, Velcro adhesive tape is used. This type of adhesive tape comprises a couple of tapes. One face of the tape is coated with adhesive film and the opposite face is coated with floss. In the fixing process, one tape is adhesive bonded to the working platform and the other is adhesive bonded to honeycomb core with the adhesive film side first. Then the honeycomb core piece is joins to the working platform. Now the flossy sides of both tapes are bonded. In this way, the honeycomb core work piece is fixed on working platform, as shown in Fig. 2.

The flossy layer of Velcro tape is about 0.8 mm in height in the free state and is prone to distort while cutting force changes. During NC machining process, the cutting force changes rapidly along with the change of tilt angle of cutter

Contributed by the Manufacturing Engineering Division for publication in the ASME Journal of Manufacturing Science and Engineering. Manuscript received March 12, 2004; final revision received March 25, 2005. Review conducted by: S. J. Hu.

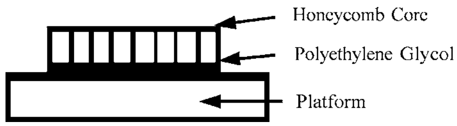

Fig. 1 Polyethylene glycol method

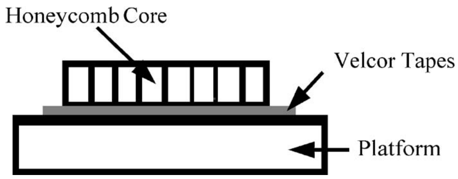

Fig. 2 Adhesive tape method

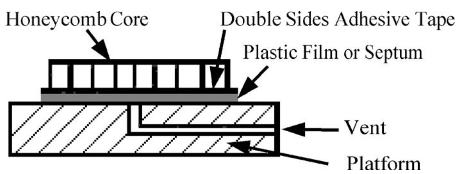

Fig. 3 Vacsorb method

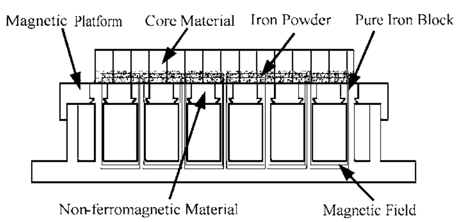

Fig. 4 Principle and structure

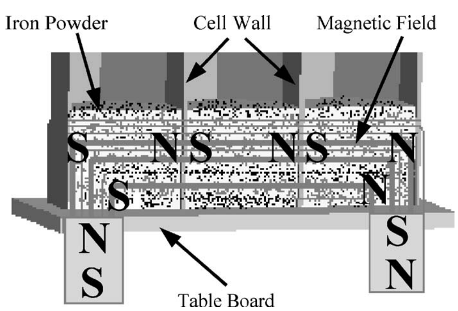

Fig. 5 Distribution of magnetic poles

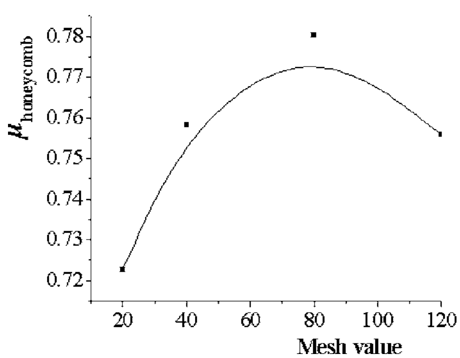

Fig. 6 Test result for honeycomb core

and the height of honeycomb core material. As a result, the height of the flossy layer also changes. So the Z direction (along with the axis direction of honeycomb core cell) shaping error of work piece induced by the flossy layer is inevitable.

Using this method, tolerance is commonly within the range from ±0.5 to ±0.8 mm and preparing time is about 4–6 h.

(3) Vacsorb method. In this method, plastic film or septum made by fiber reinforced plastic is first adhesive bonded to the core work piece face, which is opposite the machining face. Then vacuum the gap between working platform and the film or septum. While the machining process is finished, the film or septum would be taken off. Principle illustration is shown in Fig. 3.

Although the third method provides a relative rigid bonding compared with the second method, the reliable adhesive bonding between core material and plastic film or septum is also difficult to achieve because the section area of honeycomb core is too little to make effective contact.

The abovementioned three methods all use adhesive materials, which claim rigorous cleaning procedure including pretreatment and after treatment. Further, more adhesive material cannot be recycled. In addition, the cleaning process often includes the use of chemical organic solvent, which is harmful to the workers' respiratory system. As a result, workers are often tearful and coughing.

The new method based on the principle of magnetic field and friction force uses iron powder as the medium to achieve fixture, and its cost for iron powder is only about 200 RMB for each airplane. Consequently, cost can be greatly reduced compared with expenditure for adhesive material, which is about 37,500 RMB in China for each airplane. Further, more iron powder can also be recycled and does no harm to workers. So this method takes a great step towards cheap tooling and no harm to workers.

3 Fixture Principle

The operational principle of the new method is shown in Fig. 4. In this method, a special magnetic platform is designed and used. This platform uses nonferromagnetic material (copper or stainless steel) as matrix and some pure iron blocks are embedded in the platform. The pure iron blocks are used as magnetic poles to lead the magnetic field through the working platform to the iron powder.

The fixing process of the new method includes three steps. The first step is to put the honeycomb core work piece onto the magnetic working platform. The second step is to pour iron powder into cells of the honeycomb core work piece at the desired height while the magnetic field switches off. The third step is to activate the magnetic field control part to produce a closed magnetic field, which flows through magnetic poles, magnetic platform, iron powder, and honeycomb core work piece. At this condition the honeycomb core work piece is fixed.

3.1 Mechanism of Friction Force Generation. Different from the adhesive bonding of traditional methods, the honeycomb core work piece will be fixed by resultant friction force in the new method.

Once iron powder is poured into the honeycomb core cells, it is separated into isolated iron powder elements by honeycomb core cell walls. As soon as magnetic field is introduced, iron powder elements will be magnetized. The distribution of magnetic poles of iron powder elements is shown in Fig. 5. From the illustration we know that the magnetic poles at both sides of each cell wall are N and S, respectively. With mutual attraction of N and S magnetic poles, vertical pressure is loaded onto honeycomb core cell walls. When the work piece has a relative motion tendency during the machining process, two types of friction force will

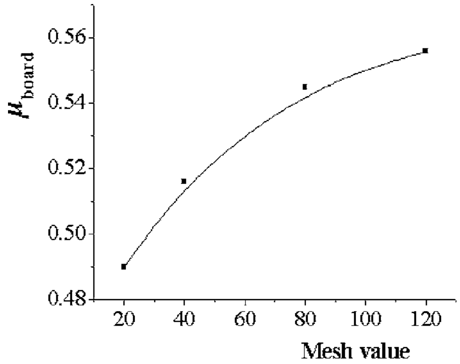

Fig. 7 Test result for table board

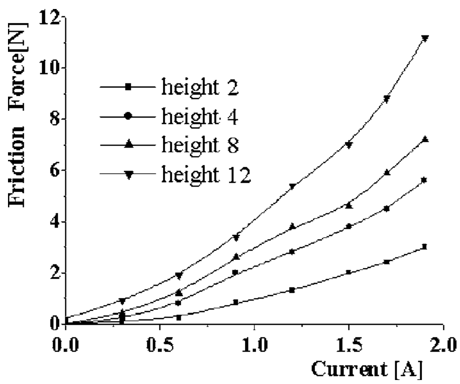

Fig. 8 Relationship of friction force and iron powder height

occur. One type is between iron powder elements and cell walls. The other is between work piece and working platform. Once the machining load is counteracted effectively by the resultant friction force, the work piece will be fixed reliably.

For different types of honeycomb core material, mechanical properties vary dramatically. So the required cutting force is also different for each honeycomb core material. In order to counteract the varied cutting force of different honeycomb core materials, the resultant friction force should also be controllable to achieve reliable fixture.

3.2 Contributing Factors of Friction Force. In order to effectively control resultant friction force, let us analyze contributing factors of friction force with Eq. (1) and Eq. (2) [8] in advance. From the above equations, we know that the main factors are friction coefficient μ, magnetic induction intensity B and effective section area S. For this method, friction coefficients include two kinds. One is between iron powder elements and honeycomb core cell walls. The other is between the honeycomb core work piece and platform. Effective section area S relates to the height of iron powder and increases along with the height increases

$$f = \mu \cdot F_{\text{pressure}} \tag{1}$$

$$F_{\text{pressure}} = \frac{B^2 \cdot S}{\mu_0} \tag{2}$$

Now let us analyze how three contributing factors influence friction force, respectively.

3.2.1 Friction Coefficient. Friction coefficient is determined by material property and surface shape. For the new method, honeycomb core material and platform is unchangeable. So the only changeable factor is the shape of iron powder. In fact, what can be changed for controlling friction coefficient is only the diameter of the iron powder particulate, i.e., granularity of iron powder.

Let $\mu_{\text{honeycomb}}$ be the friction coefficient between the iron powder and the cell wall, and μ_{board} be the friction coefficient between the honeycomb core work piece and the working platform. Experiments on determining the relationships between the friction coefficients and the iron powder granularity have been carried out. In this experiment only four types of iron powder, limited for market supply, are tested. The four types are 20 mesh, 40 mesh, 80 mesh and 120 mesh, respectively.

Figure 6 shows the experimental result of honeycomb core material, NRH-3-48 (0.05), and Fig. 7 shows the tested result of the working platform. For honeycomb core material, friction coefficient gets the max value while iron powder is 80 mesh. For the working platform, friction coefficient increases while iron powder becomes finer and finer within experimental iron powder.

In order to meet demands of machining and assembling of paper honeycomb core work piece, two principles for choosing iron powder should be abided, and are listed below:

(1) Max friction coefficient between cell wall and iron powder should be considered.
(2) Granularity should be as big as possible to ensure iron powder, left in core material, can be conveniently cleaned.

Considering the abovementioned principles, 80-mesh iron powder is preferred as the medium.

3.2.2 Magnetic Induction Intensity. Magnetic induction intensity is controlled from two aspects. One is the structural parameter including length of magnetic poles and air gap between each segment. The other one is the capability of the magnetic body to the excite the magnetic field.

When the magnetic body is given, the length of magnetic poles and air gap are primary contributing factors. These two factors affect magnetic induction intensity by changing total magnetic resistance of closed magnetic field loop, as Eq. (3), shown in Ref. [8]. In this equation, l_i, μ_i, and S_i denote length, magnetic permeability and effective area of each component of the whole loop, respectively. As for the new fixture system, total magnetic resistance is composed of three parts, including magnetic pole, air gap

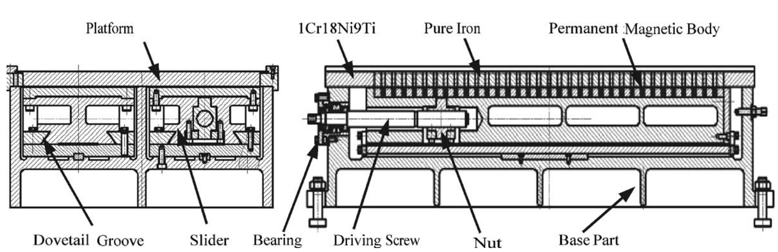

Fig. 9 Fixture equipment

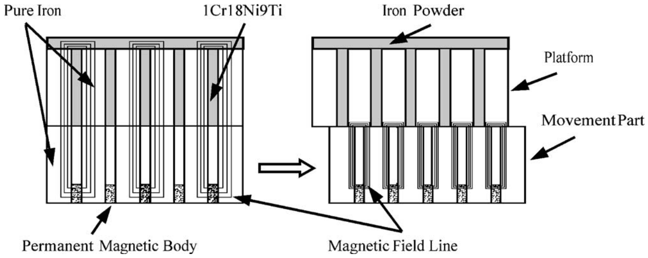

Fig. 10 Control principle

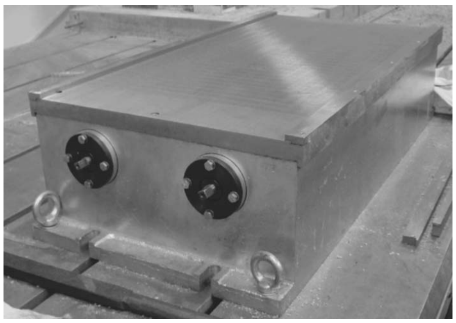

Fig. 11 Fixture equipment

Fig. 12 Machining results

and iron powder. Among them, magnetic permeability μ_i of magnetic pole and iron powder are about 10^3 times larger than the value of air gap. That means length of air gap l is the most important factor for total magnetic resistance. In order to get minimum value of magnetic resistance, the length of air gap should be set as small as possible. Although the length l and section area S of magnetic pole do not have obviously the effect as air the gap does, magnetic induction intensity decreases while length and section area of the magnetic pole increase.

$$R = \sum_{i=0}^{2} \frac{\ell_i}{\mu_i S_i} \tag{3}$$

When structure parameters are given, the magnetic body is the main factor. Traditionally, there are two methods to get magnetic field. One is the permanent magnetic body and the other is the electric exciting coil.

As for permanent magnetic body, magnetic induction intensity B_g is controlled by choosing work point, changing section area A_m and length ℓ_m along with vector direction. Magnetic induction intensity increases as section area and length increase, as shown in Eqs. (4) and (5) in Ref. [9], until the magnetic circuit is saturated.

$$A_m B_m = F A_g B_g \tag{4}$$

$$H_m \ell_m = f B_g \ell_g \tag{5}$$

As for electric exciting coil, magnetic induction intensity B is controlled by adjusting electric current intensity I and turn number N of the exciting coil. Magnetic induction intensity increases as electric current intensity and turn number increase, as shown in Eq. (6) of Ref. [8], until the magnetic circuit is saturated.

$$B = \frac{NI}{S} \tag{6}$$

3.2.3 Effective Section Area. Effective section area refers to the contact area between iron powders and honeycomb core cell wall. Effective section area is linear with the height of iron powder. So influence of effective section area is equivalent to the influence of iron powder height. It can be deduced from Eq. (3) that the total magnetic resistance decreases while iron powder height increases.

In order to study how iron powder height affects friction force, an experiment has been done to determine the resultant friction force with different iron powder height and magnetic induction intensity. Because the value of permanent magnetic body is inconvenient to adjust, in this experiment an electric magnetic coil, with 2340 turns, is used. The type of tested honeycomb core material is NRH-3-48 (0.05) and its cross section dimension is 65 mm $\times$ 150 mm. The height of iron powder is 2, 4, 8, and 12 mm, respectively, which are signed as "*height*" in Fig. 8.

From the experiment we find that when the height of iron powder is greater than 2 mm and the magnetic induction intensity of iron powder is larger than 0.1 T, iron powder will be solidified with the honeycomb core work piece. At this condition, even the honeycomb core work piece is pulled up by the cutting force, the iron powder does not drop freely under the effect of gravity.

4 Equipment Design and Application

The fixture system includes fixing equipment and NC iron powder feeder. The NC iron powder feeder is used to evenly pour iron powder with desired height, and the fixing equipment is used to reliably fix the paper honeycomb core work piece.

4.1 Fixing Equipment. Based on the fixture principle analyzing and feasibility testing, fixing equipment of paper honeycomb core work piece for high-speed NC machining is designed using a permanent magnetic body, and its structure is shown in Fig. 9.

This fixing equipment consists of three parts base part, movement part and working platform. Base part is made of aluminum alloy and comprises two floors. The nether floor supports the mass of the equipment and keeps the whole equipment as a rigid body.

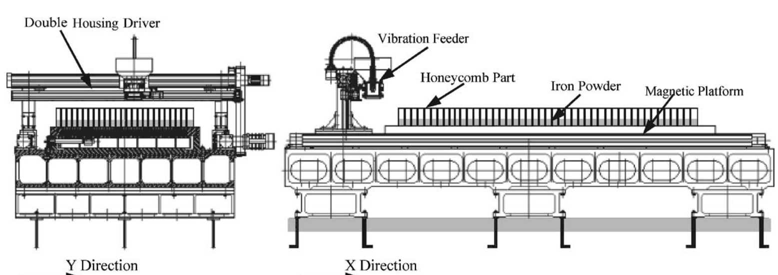

Fig. 13 Structure of the feeder system

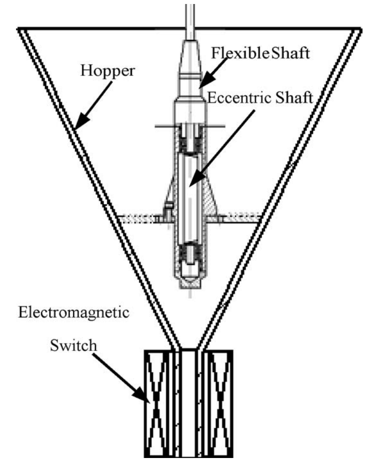

Fig. 14 Structure of vibration feeder

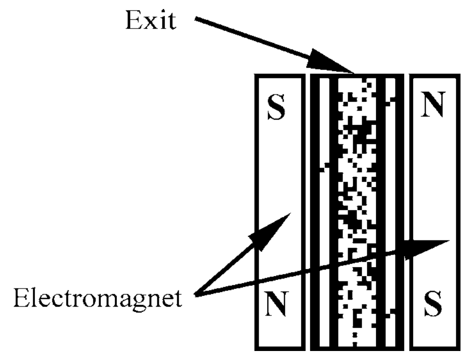

Fig. 15 Structure of switch

The upper floor is a cavum where the movement part is placed.

Movement part comprises a driving screw, nut, bearing, slider block and a plate with dovetail groove. On the upper surface of the slider block, pure iron blocks and permanent magnetic bodies are placed alternately. The movement part is used to control the magnetic circuit. The controlling principle is shown in Fig. 10. When pure iron blocks both in platform and on slider block are in superposition in the vertical direction, magnetic field lines will go through iron powder. At this condition, iron powder is magnetized and the honeycomb core work piece can be reliably fixed on the platform. When the movement part moves a designed space along the horizontal direction, magnetic field lines will not go through iron powder anymore, i.e., iron powder will not be affected by additional magnetic field. Consequently, the honeycomb core work piece can be taken off freely.

The working platform is a composite structure, whose matrix material is stainless steel and pure iron blocks are embedded in with equal space. Pure iron blocks are used to lead magnetic field through the platform and into iron powder.

The manufactured equipment, whose effective working area is 500 mm $\times$ 1000 mm and mass is about 500 kg, is shown in Fig. 11. Using this equipment, some cutting experiments are carried out to validate the fixing effect. In the cutting experiment, turning speed and feed speed of five-axis high-speed milling machining are 15,000 r/s and 1500 mm/min, respectively. Type of paper honeycomb core material is NRH-3-48 (0.05). Figure 12 shows the cutting results, and their Z direction shaping errors are all within ±0.1 mm, Which is much satisfied compared with the tolerance range, about ±0.5 mm, of traditionally used methods.

It can be confirmed from the cutting result that the new fixture method based on magnetic field and friction force can fixture paper honeycomb core work piece reliably and the precision of machining is greatly improved.

4.2 Numerical Control Iron Powder Feeder System. In the new fixing method, the height of iron powder has a great effect on resultant fixing force. In order to achieve even pouring of iron powder with the desired height, the NC iron powder feeder is designed and manufactured. Structure of NC iron powder feeder equipment is shown in Fig. 13, and its main components include double housing driver, vibration feeder and software system. The key technologies are vibration feeder and pre-compaction method. The software system is used to control the motion of the driver and the switch pouring state of feeder.

4.2.1 Vibration Feeder. The vibration feeder is designed as a container and used to pour iron powder into the honeycomb quantitatively. As shown in Fig. 14, the vibration feeder is composed of hopper, vibration exciter and the electromagnetic switch. The vibration exciter comprises the motor, flexible shaft and eccentric shaft. The eccentric shaft is used to excite vibration while the motor drives the flexible shaft with the designed rotate speed. The vibration frequency can be adjusted by changing the rotate speed of the motor using a transducer. It is determined by pouring experiment that iron powder can be evenly poured when the rotate speed reaches 2200 r/min.

The exit of the hopper is a groove whose width is 2 mm and length is 100 mm. This is different from the hopper [10] whose exit is a pair of meshed plates; one is fixed while the other is movable. With the former design, the exit is often blocked by iron powder and the movable plate is often stuck. Thus pouring process cannot be achieved.

Compared with the former design, another difference is the electromagnetic switch. In the present design, the switch is a pair of electromagnets. The distribution of magnetic poles is shown in Fig. 15. When the switch has power on, iron powder in the exit is magnetized and solidified. In this condition, the exit is blocked. When the switch has power off, iron powder can flow freely.

Using this numerical control feeder system, iron powder can be evenly poured and the switch can be easily controlled. The relationship between iron powder height and moving speed of the feeder is obtained and shown in Fig. 16.

4.2.2 Precompaction. In order to meet aerodynamics demands, both top and bottom surfaces should be machined to designed shape. Although the top and bottom surfaces of honeycomb core material are considered as plane theoretically, distortion will be formed under a free state, after the machining process of the first surface. Therefore, during the pouring process of iron powder for machining of the second surface, the machined surface of honeycomb core work piece cannot entirely touch with the platform. As a result, a gap between honeycomb core and platform

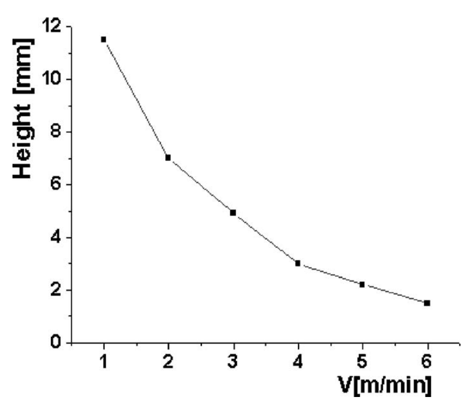

Fig. 16 Relationship between iron powder height and move speed of feeder

will form. At this condition, iron powder will flow into the gap during the pouring process. When the magnetic field is introduced, the honeycomb core will be fixed and the gap will be transformed to the Z direction error of the machined work piece.

In order to eliminate this type of error, we must get rid of the gap between the honeycomb core and platform before pouring process. That is, the pre-compaction technology is necessary.

Paper [10] developed a pre-compaction method using an air bag. In this method, the sand sack should be placed as soon as the air bags lift. Workers say that this operation is too difficult for them to control. Consequently, the effect of precompaction cannot be achieved. Now we use several special stainless steel blocks to achieve pre-compaction process. Stainless steel blocks are specially formed like the honeycomb core to ensure the iron powder goes through and drops into the paper honeycomb core cells directly. During pre-compaction process, stainless steel blocks are placed on the honeycomb core work piece at serials designed points. The locating points of stainless steel blocks are selected according to the "N-2-1" principle [11] and the optimization methods developed in paper [12]. Under gravity of stainless steel blocks, the gap between the work piece and platform is eliminated. Thus workers are easy to operate and control.

Using the new fixing method, associated with the numerical control feeder, the preparation time is reduced from 4 to 1 h for a stab paper honeycomb work piece, and the machining precision is improved greatly. All the related equipments have been widely used in the China Chendu Airplane Company.

5 Conclusion

In this paper, a new fixture system of paper honeycomb core for high-speed NC machining is presented. The new method aims to improve fixing reliability, final machining precision of paper honeycomb core work piece and reduce preparing time and cost of machining process. This method uses iron powder, which can be magnetized by additional magnetic field, as a medium to form two types of controllable friction force. With resultant friction force, cutting force can be counteracted effectively. Thus honeycomb core can be fixed reliably. This way, traditional adhesive bonding is abandoned. Then contributing factors of friction force, such as friction coefficient, magnetic induction intensity and effective section area, are analyzed to determine relationships between friction force and each factor. Based on the principle of analyzing and feasibility testing, fixture equipment is designed and manufactured. Using this equipment, paper honeycomb core work pieces are machined and their Z direction machining errors are all within ±0.1 mm. At the end of this paper NC iron powder feeder system, which ensures even pouring of iron powder, is also introduced.

Along with popularizing of this new method, fixture expenditure will be decreased from 37,500 RMB to 200 RMB for each airplane of current model, processing cycle will be greatly shortened and workers will have a more healthy working environment.

Acknowledgment

The authors would like to thank the participation of Dr. Wu Fuzhong in this research. Also, discussions with Jia Shushi are highly appreciated.

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