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In-process monitoring and control of microassembly by utilising force sensor

S. Tangjitsitcharoen [a,*], P. Tangpornprasert [b], Ch. Virulsri [b], N. Rojanarowan [a]
[a] Department of Industrial Engineering, Faculty of Engineering, Chulalongkorn University Bangkok, 10330 Thailand
[b] Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University Bangkok, 10330 Thailand
* Corresponding author: E-mail address: Somkiat.T@eng.chula.ac.th

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Analysis and modelling

ABSTRACT

Purpose: The aim of this research is to develop an in-process monitoring system to control the position of the shaft within a tolerance of ±2.5 μm regardless of any conditions of the geometries of the shaft and the thrust plate.
Design/methodology/approach: To realize an automated and intelligent microassembly process, a method has been developed to monitor and control the position of the shaft in the plate of the high-precision spindle motor for hard disk drive in order to reduce the shaft high problem. The force sensor is utilized and attached on the table of the microassembly machine under the jig of the plate to monitor the in-process pressing force. The experimentally obtained pressing force depends on the variations of the tolerance fitness and the geometrical roundness of the shaft and the plate but it is increased immediately when the shaft touches the stopper on the jig as the setting point. Hence, a method proposed introduces the reference voltage as the threshold value, which is calculated and obtained by taking the differentiation of the in-process pressing force. A slope detector is developed to calculate the output voltage based on the in-process pressing force, and the motor driver of machine is controlled when the obtained output voltage is larger than the reference voltage.
Findings: It is proved that the shaft high problem is well controlled and reduced by the method developed regardless of any combinations of the geometries of the shaft and the plate.
Practical implications: In this research, the microassembly process of the shaft into the plate of high-precision spindle motor for hard disk drive is showed.
Originality/value: This paper has shown the developed the in-process monitoring system and control the manufacturing process automatically.
Keywords: Monitoring; Microassembly; Pressing force; Shaft; Plate

1. Introduction

As the fully automated and intelligent manufacturing is expected to be realized in the near future, it is necessary to develop the in-process monitoring system and control the manufacturing process automatically. In case of microassembly process, it is recognized as one of the most important processes, which requires reliable sensing or monitoring, since it plays the key role not only in quality of product but also production rate as well as production cost. The sensors have a greater importance than in monitoring of machine tools, especially in automatic assembly [1]. The reasons are that the assembly operations are generally complex. Even if the assembly process is operated in a structured working environment, some variables such as part tolerances, positioning errors, unknown positions of parts, always influence the process where sensors are necessary. Therefore, the good insertions of the shafts in to the plates can result in very different signals [2]. Hence, it is difficult to extract a significant feature for the process and the monitoring will only be effective when the geometrical parameters are nearly constant. It means that the industrial applications are few, especially in microassembly process or high-precision assembly process which needs the in-process monitoring and control during the process.

Extensive research efforts have been devoted so far to develop sensors and methodologies for microassembly [3-6]. The sensors based on modern technologies or sensors which request proper algorithms to process the outputs such as force sensor, torque sensor, and tactile sensor, are gradually spreading in the industrial practice. It is already known that the force sensor is able to generate a signal corresponding to the pressing force exerted between two objects in a contact. It is one of the first solutions adopted to obtain a powerful and reliable feedback in automated assembly [7-10]. The artificial neural networks and clustering techniques have been used in different ways in sensor technology by many researches [13-15]. However, the preliminary experiments for specific cases of different conditions are always required to set up the database and train the system.

In this research, the microassembly process of the shaft into the plate of high-precision spindle motor for hard disk drive is studied and monitored. Presently, the torque sensor, which is attached in the microassembly machine, is normally used to control the position of the shaft during the assembly by setting the limit of torque to stop the motor driver of machine. However, the position of the shaft in the plate is still necessary to monitor and control because of the geometrical parameters, which cause the rejects due to the shaft high problem and the damage of jig. Since the shaft high problem is still the major limitation on the productivity of high-precision spindle motors, which is measured from the setting point at -4.5μm with a tolerance of ±2.5 μm. In fact, the shaft already touches the stopper on the jig which is the setting point but the shaft is still pressed because the torque has not been reached the setting value yet due to the variations of the tolerance fitness and the geometrical roundness of the shaft and the plate.

Hence, the aim of this research is to develop an in-process monitoring system to control the position of the shaft within a tolerance of ±2.5 μm regardless of any conditions of the geometries of the shaft and the thrust plate. The force sensor is adopted here to monitor and investigate the shaft high problem in order to reduce the problems and increase the reliability of automated and intelligent microassembly machine. A method proposed introduces a reference voltage as the threshold value, which is calculated and obtained by taking the differentiation of the in-process pressing force. A slope detector is developed to calculate the output voltage based on the in-process pressing force, and the motor driver of machine is controlled when the obtained output voltage is larger than the reference voltage.

2. In-process monitoring of microassembly process

Monitoring of In-Process Pressing Force

The in-process pressing forces that occur during the assembly process are especially considered as one of the key process variables. The in-process pressing force diagram is described as shown in Fig.1. The in-process pressing force is equal to the friction force (f) while the pressing speed is constant.

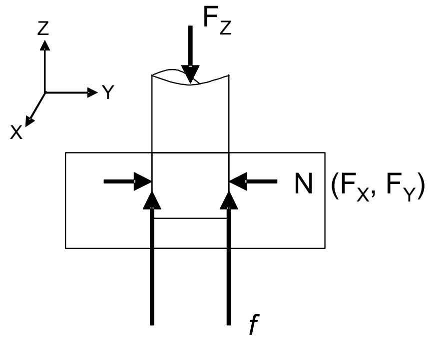


Fig. 1. Illustration of the pressing forces occurred during the assembly process

For high-precision spindle motors, the tolerance fitness of the shaft and the plate is ±0.5 μm and ±3.0 μm respectively, which is very small. However, that tolerance fitness may cause not only the shaft high problem but also the misalignment between the shaft and the plate as well as the deformation of the plate. Therefore, the normal force (N) is expected to be varied by the tolerance fitness. It means that the tolerance fitness affects the magnitude of the pressing force (Fz) directly. Hence, it is necessary to investigate the pressing force during the assembly process in order to control the shaft high problem.

Slope Detection of In-Process Pressing Force

Since the shaft and the plate are high-precision parts with a small tolerance fitness. Hence, it is expected that the in-process pressing force is increased differently based on the variations of the tolerance fitness and the geometrical roundness of the shaft and the plate. But it will be increased immediately when the shaft touches to the stopper on the jig as the setting point. In case of shaft high problem, the in-process pressing force may damage the stopper because of the in-process pressing force which still occurs and increases continuously by the motor driver of the machine until the pressing force reaches the setting value.

Due to the change of in-process pressing force as expected during the process, the slope of in-process pressing force is also expected to be increased immediately as the in-process pressing force increases when the shaft touches the stopper. Hence, the slope detection method is then developed to monitor and differentiate the in-process pressing force obtained while the shaft is being pressed into the plate. The differentiation method is proposed to calculate the slope of in-process pressing force in order to control the position of the shaft when it touches the stopper, which is expressed by,

$$X = \Delta F / \Delta t \qquad (1)$$

where X, ΔF, and Δt are the slope value of in-process pressing force, increment of the pressing force and the pressing time, respectively. The obtained slope value X is converted to the output voltage in order to find out the reference voltage as the threshold value to control the motor driver of the machine when the shaft touches the stopper.

Design and Development of Slope Detector

According to the above mentions, the slope detector is designed and developed by utilizing the principle of the differentiation of the in-process pressing force, and employing the differential circuit.

It is expected that the slope detector will reduce the rejects due to the shaft high problem. Hence, the slope detector is designed and developed to stop the motor driver of the machine when the shaft contacts the stopper, and move the motor driver up and go back to the initial position.

The details of the slope detection circuit developed are expressed in the Fig. 2. Figure 2 illustrates the slope detection circuit developed which has three main sections. The first section is a low-pass filter with the cut-off frequency of 25 Hz, which has a gain of 10 times.

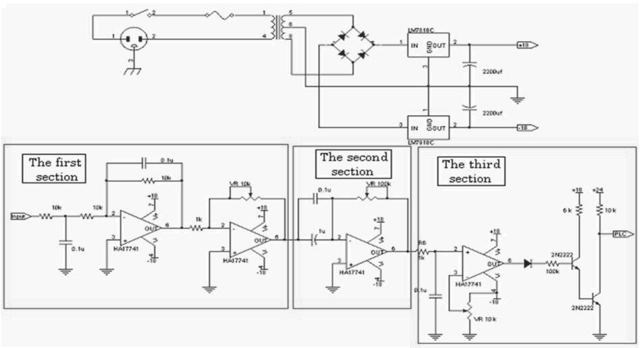


Fig. 2. Illustration of the developed slope detection circuit

The second section is a differential amplifier. It differentiates the in-process pressing force signals and gives the constant output voltage depending on the shapes of input signals. And, the third section is a comparator circuit, employed to compare the constant output voltage with the reference voltage which is determined as the threshold value of the system.

The slope detector has been examined and calibrated in advance. Hence, the output voltage obtained from the slope detector is believable.

3. Experimental equipment and setup

In order to reduce the shaft high problem and obtain the reference voltage, the 3-axis force sensor is employed to monitor the in-process pressing forces occurred while the shaft is pressed into the plate. It is installed on the table of the microassembly machine under the jig of the plate as shown in Fig. 3. Hence, the in-process pressing forces can be well obtained and measured during the assembly process. The microassembly machine equipped with the developed slope detector is shown in Fig. 4.

The diameter of the shaft is 3.971 mm with a tolerance of ±3.0 µm. The diameter of the hole of the plate is 3.963 mm with a tolerance of ±3.0 µm. The measuring point is set at -4.5µm with a tolerance of ±2.5 µm in the plate as shown in Fig. 3.

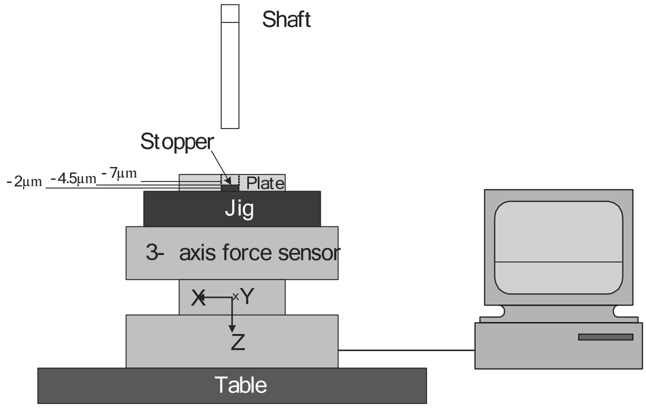


Fig. 3. Illustration of 3-axis force sensor installed in the microassembly machine

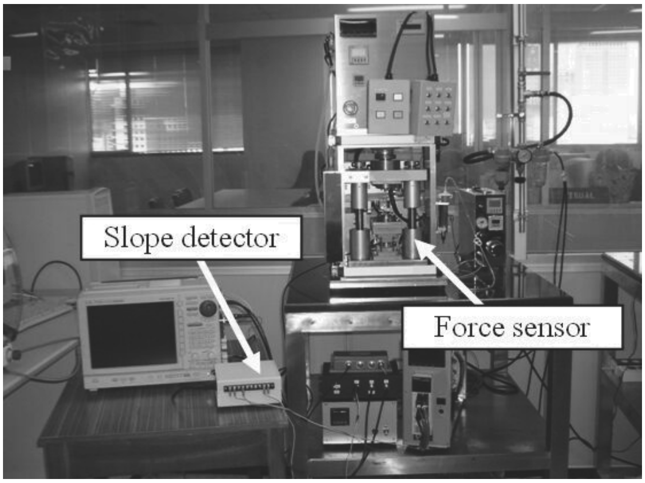


Fig. 4. Illustration of the microassembly machine equipped with the slope detector

The following procedures are adopted here to monitor the in-process pressing force.

1. Check the geometrical roundness of the shaft and the plate before the experiment in order to examine the machining geometry and dimension by the roundness tester.
2. Start pressing the shaft into the plate on microassembly machine.
3. Record the in-process pressing forces in the PC, and simultaneously differentiate the in-process pressing force and convert the obtained slope value to the output voltage by the slope detector.
4. Plot the corresponding time records of the obtained output voltages and the in-process pressing forces.
5. Measure the position of the shaft in the plate by digital height checker.
6. Find out the relation between the in-process pressing force and the shaft high problem.
7. Define the threshold value of the in-process pressing force that causes the shaft high problem.
8. Develop the algorithm to control the motor driver of microassembly machine to reduce the shaft high problem.

4. Experimental results and discussions

Relation between Shaft High and In-Process Pressing force

The in-process pressing forces obtained during the assembly process are low-pass filtered and amplified prior to digitization within personal computer. The typical example of the experimentally obtained results of the in-process pressing force is shown in Fig. 5. The in-process pressing force Fz is the largest one among three components of the in-process pressing forces. Therefore, the in-process pressing force Fz is employed to monitor the problem of shaft high mainly.

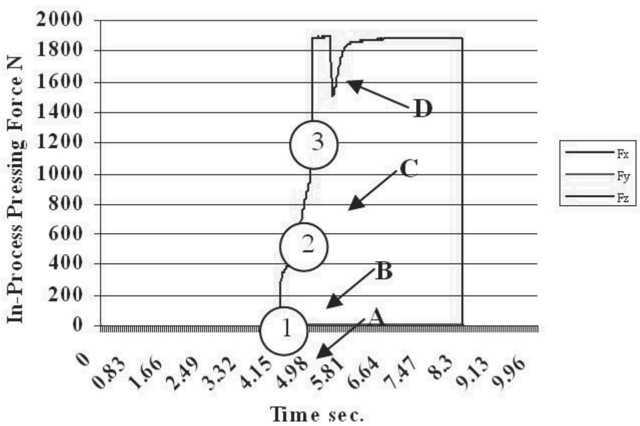


Fig. 5. Typical example of the experimentally obtained in-process pressing forces

Figure 5 illustrates the experimentally obtained in-process pressing force which has three main slopes and four critical points (A, B, C and D). The relation between the in-process pressing force and the shaft high problem can be considered and described by utilizing the Fig. 5. The experimentally obtained in-process pressing force has the different slopes during the assembly, which are classified into three intervals. The third interval has the steepest slope as compared to the others, but the first interval is steeper than the second one.

The first slope occurs while the shaft is touching the plate, and the in-process pressing forces happen from A to B as shown in Figs. 5 and 6 (a). The second slope happens from B to C when the shaft is pressed into the plate as shown in Figs. 5 and 6 (b). The critical point C is that the shaft is pressed into the plate, and touches the stopper on jig as shown in Fig. 6 (c). However, the motor driver is still pressing the shaft into the plate for the time being until the in-process pressing force reaches the setting value. The third slope is hence from C to D which can cause the shaft high problem as shown in Fig. 6 (d). It is therefore desirable to stop the shaft at the point C in order to avoid the problem of the shaft high by utilizing the slope detection. Since each interval of the in-process pressing force has the significantly different slopes, especially the third one which is the steepest one as shown in the Fig. 5.

The change in the slope of in-process pressing force is therefore required to detect and proposed to improve the shaft high problem regardless of the variations of the tolerance fitness and the geometrical roundness of the shaft and the plate, which are uncontrollable. Figure 7 shows the example of the experimentally obtained geometrical profiles of the shafts and the plates measured by roundness tester. Even though the slopes of the in-process pressing force depend on the above variations but the third slope is the steepest one as compared to the first and the second slopes.

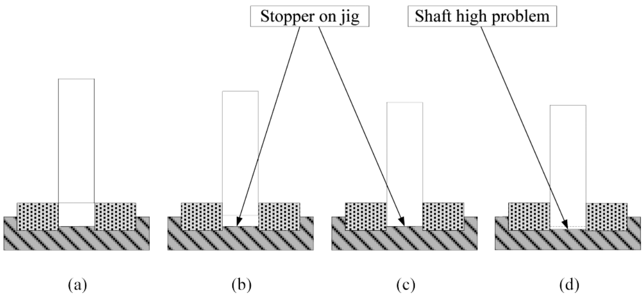
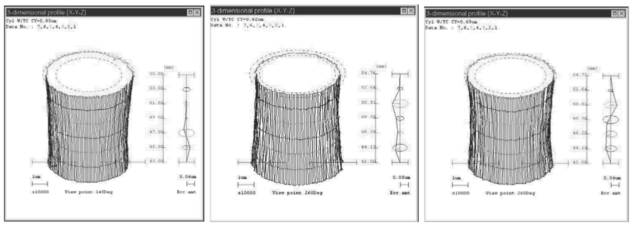
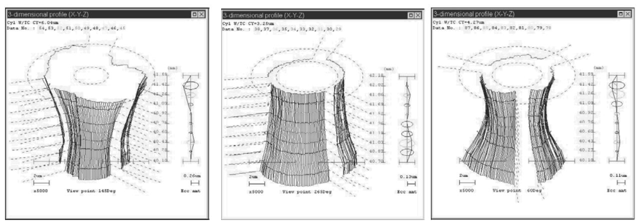


Fig. 6. Illustration of the position of the shaft in the plate during the assembly



(a) Cylindricity profile of the shafts



(b) Cylindricity profile of the plates

Fig. 7. Examples of the experimentally obtained variations of the geometrical profiles of the shafts and the plates

In order to eliminate those variations of the shaft and the plate, the reference voltage is hence proposed to be calculated automatically and obtained individually from the obtained output voltage of the first slope for each assembly of the shaft and the plate, and multiplied with the safety factor of 20 percent. Hence, the obtained reference voltage is varied based on the individual assembly of each shaft and each plate.

Evaluation of Slope Detector and Reference Voltage

The slope detector is designed and set to stop the motor driver which is pressing the shaft down when the shaft contacts the critical point C in order to move the motor driver up and go back to the initial position. The principles and the procedures of the slope detection method developed are illustrated in Fig. 8. Once the in-process pressing force signals are obtained, the pressing force signals will be low-pass filtered and differentiated. The constant output voltage obtained from the differentiation is compared to the obtained reference voltage (Vref). And, the signal of 24 voltages will be fed into the microassembly machine in order to control the motor driver when the obtained constant output voltage is larger than the obtained reference voltage. The algorithm is developed and proposed to control the motor driver as shown in Fig. 9.

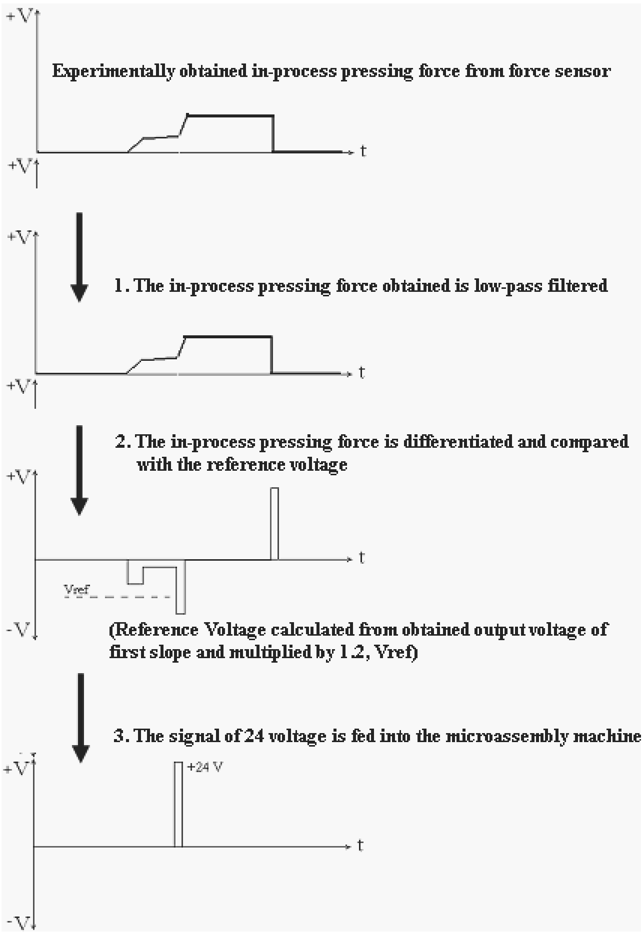


Fig. 8. Illustration of the principles and the procedures of the developed slope detection method

The series of experiments are conducted to evaluate the performance of the slope detector and the reference voltage by checking and verifying with the results of the shaft high. The experimentally obtained in-process pressing force by using the developed slope detector is shown in Fig. 10. It is understood that the shaft is controlled and stopped when it contacts the stopper of the jig by utilizing the slope detection.

Figure 11 shows the experimentally obtained positions of the shafts in the plates which are measured by referring to the setting point at -4.5μm with a tolerance of ±2.5 μm. The experimentally obtained average of the position of the shaft is -4.46 μm, which is close to the setting point. The experimentally obtained positions of the shafts are in the acceptable tolerance around the setting point without the rejects due to the shaft high problem.

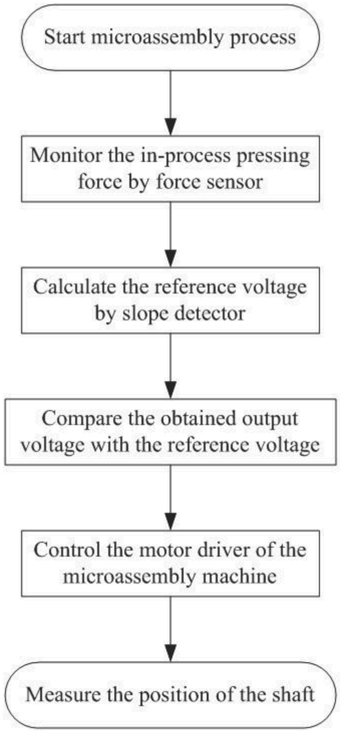


Fig. 9. The algorithm proposed to reduce the shaft high

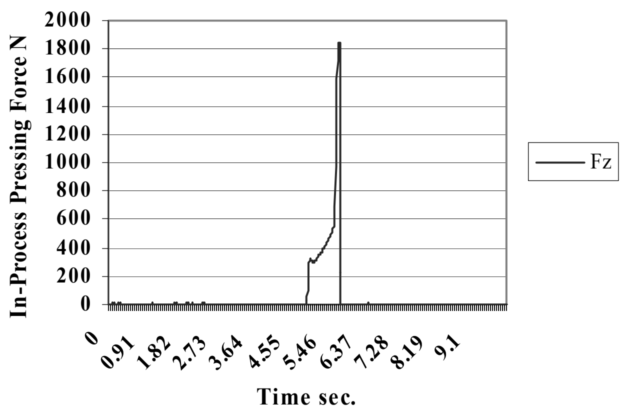


Fig. 10. Illustration of the experimentally obtained in-process pressing force by using the developed slope detector

Statistical Tests of Slope Detector

The statistical test is utilized to prove the slope detection method. The following hypotheses are tested with the significance level of 0.05. The first test is the proportion test;

Hypothesis1: H_0: **p**without = **p**with
H_1: **p**without > **p**with

where **p**without is the proportion of rejects due to the shaft high without the slope detector installed in microasseembly machine, and **p**with is the proportion of rejects due to the shaft high with the slope detector installed. The objective of the first hypothesis is to test whether the slope detector method significantly reduces the proportion of rejects due to the shaft high.

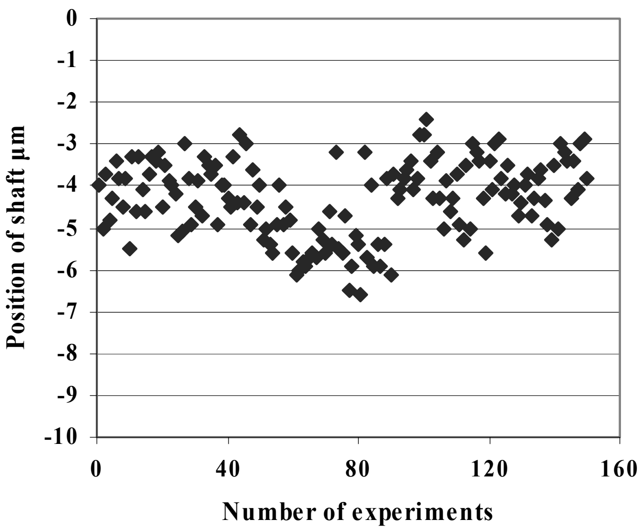


Fig. 11. Illustration of the experimentally obtained positions of the shafts in the plates by using the developed slope detector

The second test is the mean test;

Hypothesis2: H_0: **µ**before = **µ**after

H_1: **µ**before ≠ **µ**after

where **µ**before is the mean of the position of the shaft without the slope detector installed in microasseembly machine, and where **µ**after is the mean of the position of the shaft with the slope detector installed. The objective of the second hypothesis is to test whether the slope detector method significantly affects the mean of the position of the shaft.

The third test is the variance test;

Hypothesis3: H_0: $\boldsymbol{\sigma}^2$before = $\boldsymbol{\sigma}^2$after

H_1: $\boldsymbol{\sigma}^2$before ≠$\boldsymbol{\sigma}^2$after

where $\boldsymbol{\sigma}^2$before is the variance of the position of the shaft without the slope detector installed in microasseembly machine, and where $\boldsymbol{\sigma}^2$after is the variance of the position of the shaft with the slope detector installed. The objective of the third hypothesis is to test whether the variance of the position of the shaft is significantly reduced after utilizing the slope detector method.

The significance levels (p-value) from the hypotheses tests are shown in Table 1.

The experimentally obtained proportion of the rejects due to shaft high problem reduces from 19/150 when there is no slope detector to 0/150 when slope detector is utilized. The experimentally obtained proportion test shows that the proportion of rejects due to shaft high problem is significantly reduced after utilizing the slope detection method with the significance level (p-value) of less than 0.0005 as shown in Table 1. It is understood that the proportion of the shaft high decreases when the slope detector is employed regardless of any variations of the geometrical profiles and the tolerance fitness.

Table 1.
Significance level of the hypotheses tests

Hypothesis	p-value	Conclusion at significance level of 0.05
H_1: **p**without > **p**with	<0.0005	Significant
H_1: **µ**before ≠ **µ**after	<0.0005	Significant
H_1: $\boldsymbol{\sigma}^2$before ≠$\boldsymbol{\sigma}^2$after	0.014	Significant

The experimentally obtained means of the positions of the shafts are -4.32 µm with the slope detector installed, and -3.53 µm without the slope detector installed. The experimentally obtained mean test shows that the p-value of less than 0.0005 supports the conclusion that the slope detection method can control the position of the shaft as shown in Table 1. The reason is that the slope detector is designed to stop the motor driver of the microassembly machine which is pressing the shaft down when the shaft reaches the critical point C in order to move the motor driver up and go back to the initial position.

The experimentally obtained standard deviation of the positions of the shafts decreases from 0.95 to 0.76 when the slope detector is utilized. The experimentally obtained variance test shows that the p-value of 0.014 supports the conclusion that the variance of the positions of the shafts is significantly reduced after utilizing the slope detection method as shown in Table 1. The reason is that the slope detector enables the shafts to consistently stop at the setting point, which results in a significant reduction in variation regardless of the effect of the geometrical conditions of the shafts and the plates.

5. Conclusions

A method has been developed for in-process monitoring and control of the shaft high problem of the high-precision spindle motor of hard disk drive in microassembly assembly process. The force sensor is utilized and attached on the table under the jig of the plate in order to monitor the in-process pressing force. The method proposed introduces the reference voltage as the threshold value which is calculated and obtained by taking the differentiation of the in-process pressing force.

The slope detector is designed and developed to monitor and differentiate the in-process pressing force in order to calculate the reference voltage to control the motor driver of machine when the obtained output voltage is larger than the reference voltage. The performance of the slope detector is evaluated and verified with the series of experiments.

It has been proved by the statistical tests that the slope detector method significantly reduces the proportion of rejects due to shaft high by utilizing the slope detector method. The reason is that the motor driver of machine has been stopped when the shaft contacts with the stopper of the jig, and the shaft is not pressed to go further down, resulting in no rejects due to the shaft high.

Acknowledgements

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