

A hybrid approach for identification of root causes and reliability improvement of a die bonding process—a case study

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Abstract

This paper presents an industrial case study on reliability improvement of the die bonding machine in the semiconductor industry. A hybrid approach combining dynamic analysis, process decomposition, and a structured fault tree was used to analyze the die bonding process. Firstly, the process was analyzed technically and decomposed into several stages according to different motions. Then, the die movement and force balance at each stage were analyzed according to physical laws, to identify the root causes of die rotation. A structured fault tree was then constructed to trace all possible causes and effects. A qualitative approach was used to identify critical events (root causes) for further analysis. Experiments were conducted to modify the bonding process to reduce the effects of the critical events. Finally, further process modification was proposed for simplification of the fault tree. This case study combined the knowledge in control and reliability engineering and presented a hybrid approach, which is very useful for practising engineers. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Quality techniques and practices are now applied not only to the products but also to the manufacturing processes. Many versions of process improvement techniques, steps, and procedures have been defined and developed. These include Deming's 14 points for process quality improvement [1], business process reengineering [2]), and continuous process improvement ([3]). However, as pointed by Janakiram and Keats [4], few researchers or engineers use the Failure Mode and Effects Analysis (FMEA) techniques as a process quality improvement tool. As a result, they suggested its use in quality improvement programs and indicated how it could be applied.

FMEA is often applied by design engineers to assess the probability of occurrence of a failure as well as the effect of the failure. It also provides early capability assessment on high risk priority items to determine appropriate process control. Process FMEA is supposed to be a team-oriented effort that identifies potential process failure modes, assess the potential customer effects of the failures, and identifies the potential manufacturing or assembly process root causes. If potential failure modes are identified, improvement

actions should be initiated to eliminate the causes or continuously reduce their potential occurrence. However, traditional FMEA requires statistical data analysis.

One of the common problems in many industrial processes is performance inconsistency due to operation complexity. In the semiconductor industry, die bonding is one of the critical processes for producing integrated circuit (IC) chips. The die bonding machine picks up a die from a wafer and bonds it onto a leadframe. A quality measure of the bonding process is the orientation of the bonded die. As the IC becomes smaller and smaller, a higher and higher accuracy is required for the die bonding process [5]. A rotation error of less than 1° is often required for light-emitting display (LED) dies. Many existing bonding machines can't satisfy this requirement. To improve the reliability of the machine, the root causes for the irregular rotation of the die must be found.

The bonding process involves many different motions. Most of the motions are not measurable during the operation. Experience is often used in the industry to guess the causes of the observed problems and then extensive experiment is conducted to confirm the guesses. This kind of practice is time-consuming and inefficient. It is difficult and expensive to do extensive testing for every component involved. A systematic, simple, and effective method is

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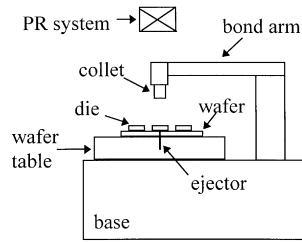


Fig. 1. A schematic diagram for the side view of the die bonding machine.

needed to identify causes of the problems and improve the reliability of the bonding process.

In this paper, we analyze the operations of the bonding process, use the concepts of fault tree and FMEA, and propose a hybrid approach to improve the quality of the bonding process. The remaining part of this paper is organized as follows. Section 2 covers the process description and decomposition. Section 3 presents the structured fault tree approach for tracing the possible causes and effects. Section 4 shows the use of FMEA concept to identify critical events. Section 5 describes the experiment to assess effects of the critical events. Section 6 proposes process modifications and re-engineering to reduce die rotation. Conclusions are provided in Section 7.

2. The die bonding process and its decomposition

The die bonding process shown in Fig. 1 involves the movements of the following components:

1. A pattern recognition (PR) system which is used to search for a die.
2. Wafer—a plate covered with a mylar sheet on which dies are stuck.
3. A movable wafer table (WT), on which the wafer is placed.
4. An ejector, which can push the die away from the wafer.
5. A bond arm, which can move vertically and rotate horizontally.

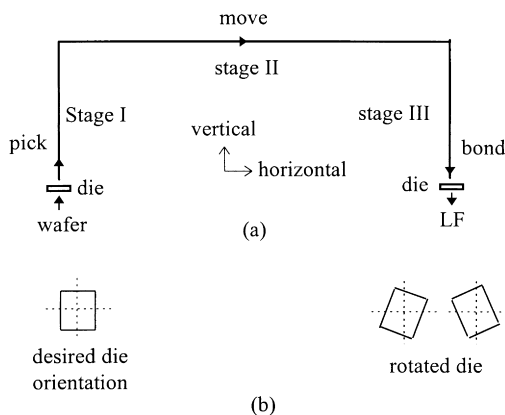


Fig. 2. (a) A side view of the die bonding process. (b) A top-down view of the die positions.

6. A collet, which is at the end of the bond arm and used to suck the die.
7. A leadframe (LF), which the die is bonded to.

The bonding process involves the searching and the picking up of a die, moving the die to a target LF, and bonding the die to the leadframe. Thus, we can decompose the die bonding process into three stages, as shown in Fig. 2a. Each of the three stages contains a series of operations listed below:

Stage I—die searching and picking:

1. A properly positioned die is selected by the pattern recognition system.
2. The wafer table moves the selected die to the pick position.
3. The collet moves above the die and the sucking vacuum is turned on.
4. The ejector moves up quickly to push the die to the collet.
5. The collet starts moving up
6. The die is sucked by the collet and moves with the collet.

Stage II—die moving:

7. The bond arm rotates horizontally from the pick position to the bond position.

Stage III—die bonding:

8. The bond arm moves down and bonds the die to the leadframe.

The die is supposed to be bonded onto a leadframe at a certain orientation. However, it often rotates during the bonding process. Fig. 2b shows the desired die orientation and the rotated dies. The requirement for bonded LED dies is that the rotation should be less than 1° , with a maximum failure rate of 5%. Many existing die bonding machines can only achieve rotations of less than 3° with the same maximum failure rate for LED dies. A significant process improvement is required to meet the desired standard. In this case study, we adopted the hybrid approach shown in Fig. 3. Based on the above process decomposition, the dynamic analysis was carried out to identify the top event for each subsystem according to physical laws governing the motions in the process. A structured fault tree was constructed logically for the top event of each subsystem. Then, FMEA concept was used to identify critical events and assess their effects qualitatively. After experiments were conducted for validation of the assessment, process modification was suggested and process re-engineering was used for eliminating some of the root causes and further enhancing reliability. The details of the approach used are outlined in the following sections.

3. The structured fault tree based on dynamic analysis

Die rotation is the *top event* for the whole bonding process. To reduce the degree of rotation, the root causes must

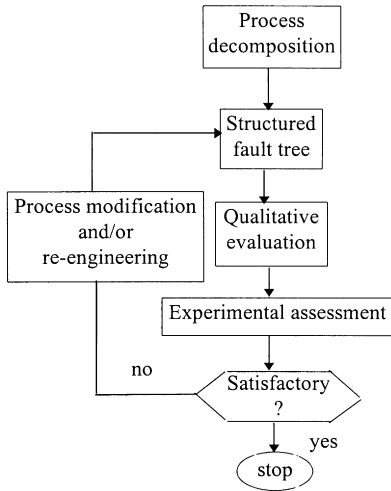


Fig. 3. Hybrid methodology for reliability improvement.

be identified and if possible eliminated. Since the process can be decomposed into three stages according to their movement, the concept of structured fault tree ([6]) used in design improvement and fault diagnosis may be used here for identification of root causes of process deficiency. However, it is still very difficult to pinpoint when and why rotation occurs due to the limitation of motion tracking in the process. This limitation makes the tree construction and analysis difficult. Fig. 4 shows the high level fault tree for the top event of the process.

According to the physical law, there must be some external force acting on the die to make it rotate in the horizontal plane. The ideal operating environment should keep the force balanced on the die along horizontal plane. This basic principle was used in our construction of the expanded fault tree. Thus, the dynamic imbalance of the external force is the top event at each stage.

3.1. Structured fault tree at stage I

The motions in stage I are supposed to be purely vertical with the details depicted in Fig. 5. The external forces on the

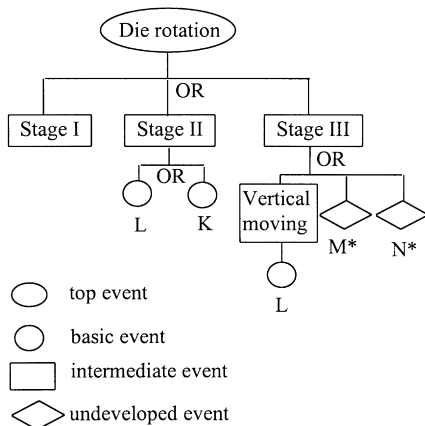


Fig. 4. System fault tree for the top event of die rotation.

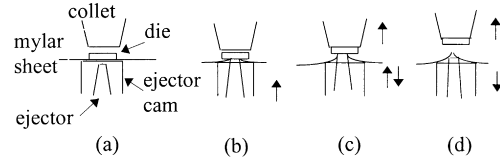


Fig. 5. Configuration of stage I—die picking process. (a) Staying on the sheet. (b) Moving towards the collet. (c) Hitting the collet. (d) Moving with the collet.

die should not cause any movement in the horizontal plane. Any horizontal torque acting on the die would deflect the die from its pure vertical motion. As shown in Fig. 6, misalignment of the collet, die, and ejector will result in a torque applying on the die and eventually cause the rotation of the die. Therefore, part misalignment is identified as the main problem to cause the rotation in stage I. The complete structured fault tree for stage I is shown in Fig. 7. The OR operation in Fig. 7 means that the output fault occurs if at least one of the input faults occurs. The definitions of the events used in Fig. 7 are defined in Table 1.

3.2. Structured fault tree at stage II

The motion in stage II is a simple rotating movement of the bond arm as shown in Fig. 8. This rotating movement can cause die slipping around the collet if the holding force is not strong enough. Thus, die slipping, i.e. dynamic imbalance of external forces, is the fundamental reason in stage II for potential die rotation. The fault tree branch for this stage can be easily established to trace die slipping as shown in Fig. 4. The symbols for basic events are also defined in Table 1.

3.3. Structured fault tree at stage III

The motion in stage III is also vertical. Similarly to the situation in stage I, the problem causing rotation is part misalignment that may cause the die to move in the horizontal plane. The structured fault tree branch for this stage is also shown in Fig. 4. Since there are still several undeveloped events, the detailed structured tree cannot be developed at this stage. Much work is required for this part in the future.

The system fault tree for the top event of die rotation is

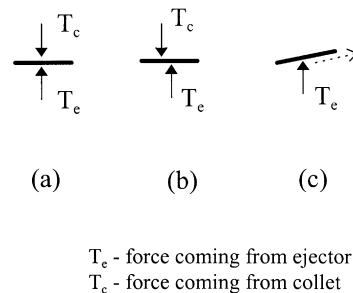


Fig. 6. Force balance diagram on the die. (a) No misalignment. (b) Ejector or collet is not centered. (c) Die is inclined.

Table 1
Definition of events

Event	Definition
A	PR system does not detect rotated die
B	Low WT moving accuracy
C	WT vibration
D	PR detection accuracy
E	Irregular die size and/or shape
F*	Non-uniform mylar sheet tension
G	Ejector misalignment
H	Ejector velocity profile
I	Bond arm moving accuracy
J	Bond arm vibration
K	Velocity profile of bond arm
L	Weak vacuum strength
M*	Inconsistent epoxy
N*	Bonding collision

completed as shown in Fig. 4 with the complete branches for stage I and stage II. The event marked with * in Fig. 4 and Table 1 indicates an event that is not further developed, either because it is not significant or because additional information is unavailable.

4. Qualitative evaluation

According to the standard fault tree analysis and FMEA methodologies, one has to estimate the frequency of occurrence of all the basic events either objectively or subjectively and efforts are then made to reduce the effects of critical or important causes. The traditional FMEA method evaluates the importance of the events quantitatively according to their probabilities of occurrence. However this method is not suitable in our case, because data is not available. Because of the limitation in time, cost, and measurement devices available, it is impossible to conduct experiments to estimate the probabilities quantitatively. A proper method is needed to evaluate the events qualitatively.

The qualitative approach should be based on the characteristics of the process. The bonding process consists of a series of operations and motions. Any fault in the early operations will be passed to the later operations and may even trigger other faults. Therefore, the operation sequence is an important characteristic of this process. It is also noted that some events are listed in more than one place in the fault tree shown in Fig. 7. For example, the event that die is not centered is listed in both branch I and branch II. The same fault may then be triggered more than once in different operations, resulting in accumulation of effects. This accumulation of effects due to repetition of the same event is the

Table 2
Offset of position control of WT

Moving distance (die size)	2	4	6	8
Position error (μm)	13	18	31	53
Relative error	5%	7%	12.2%	21%

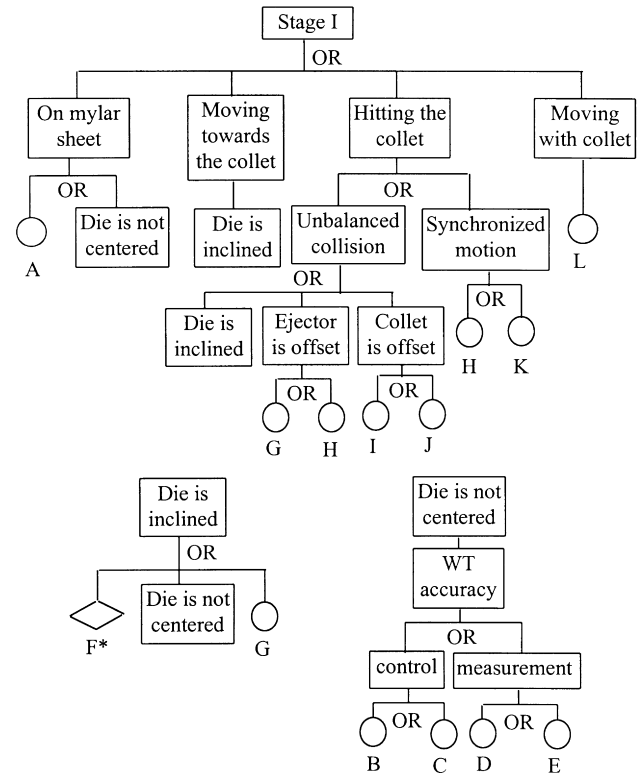


Fig. 7. Fault tree for tracing the contribution of stage I to die rotation.

second characteristic of this process. Based on these two features, the following qualitative rules were developed to assess the criticality of the events.

- An early event is more important than a later event.
- A repeated event is more important than a one-off event.

The more critical events should be given a higher priority. It is easy to discover that basic event A and intermediate event “die is not centered”, which contains the basic events (B, C, D, E), will be more important than others. Event A is the first event that may show up in the sequence of operations of the process. Events B, C, D, and E are repeated three times in branches I, II, and III. These five basic events have top priority and deserve top attention for reduction of the occurrence of the top event.

In this section, the concept of FMEA was used. However, we used process dynamics instead of statistical data analysis to assess the criticality of different events. This idea can be used in other process reliability improvement endeavors when data is not available.

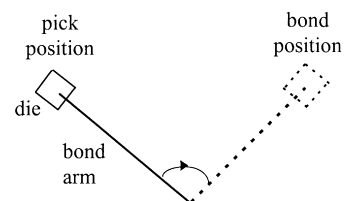


Fig. 8. Top view of the movement of stage II.

5. Experimental assessment of events with top priority

Based on the analysis in Section 4, experiments were designed and carried out to assess the effects of the events with top priority and reduce their effects.

5.1. PR system

The function of the PR system is: (1) to select a die with a rotation of less than 1° (relevant to event A); and (2) to calculate the center position of the selected die (relevant to event D). After extensive testing was conducted on the performance of the PR system, it was found that the rotation detection was not satisfactory. Many dies with rotations larger than 1° were actually selected because the PR system was incapable of processing dies with irregular sizes. An ideal LED die is a 10 mil (254 μm) square chip that has four clear cut edges and corners. Practically, a die may have non-straight edges and even missing corners. This irregularity makes die rotation detection difficult and also affects the accuracy of the calculation of the center position of the die. An unsatisfactory PR system, symbolized by events A and D, was certainly one of the main causes for large die rotation. Though die shape irregularity is the fundamental reason for the problem, it is not under the control of the company.

5.2. WT system

Events B and C represent that the WT is not controlled satisfactorily. The components that may affect the performance of the WT are the control system and the WT structure. The WT can move in both X and Y directions. A stepper motor was used to control these movements in open loop. The resolution for the stepper motor used is about 6.25 $\mu\text{m}/\text{step}$. Apparently, this control system cannot achieve a high performance due to the open loop structure. The distance between every two neighboring dies is about one die size (254 μm). The WT moves only two die sizes most of the time, except when the neighboring die has to be skipped. The moving distance of the WT should be a multiple of double die sizes. Experiment results of WT movements are shown in Table 2. Let D represent the die size and PE the position error. The relative error (RE) is calculated as $\text{RE} = \text{PE}/D$ (%). As the moving distance becomes larger, the position error accumulates and the relative error becomes larger. A larger RE means a larger offset of the die away from the pick position, i.e. a larger part

misalignment. The larger part misalignment is more likely to cause larger die rotation in the die bonding process.

In conclusion, a more effective PR algorithm that can handle the rotated die with irregular shape is needed, and the WT should be modified.

6. Process modification and re-engineering

According to the experimental results, three major modifications were suggested below to improve this situation:

- Develop a new PR algorithm that can handle the rotated die with irregular shape.
- Replace the stepper motor (open loop) with a DC servo motor (closed-loop) to improve position control ([7]).
- Re-design the WT so that it has a floating structure, to reduce the position error caused by potential material deformation.

Extensive experiments confirm the effectiveness of the new PR algorithm, which can reject the die with a rotation of larger than 1° . After a refined PR algorithm and a new WT system (control system and WT structure) were used, the position error of bonded dies was improved as shown in Table 3. The final die rotation was improved from 3° to 2° with the same failure rate. These modifications are simple enough for the users of the equipment to implement.

The procedure outlined above can be used for identification of root causes and reduction of the effects of some of these identified causes or events. However, they do not eliminate these causes. As shown in Table 3, much work was needed for further reduction of die rotation. If the fault tree can be simplified with the removal of some basic events, the process may be improved to further enhance process reliability.

The system fault tree shown in Fig. 4 consists of three branches. The branch for stage II is very simple, which may be removed or combined with other branches. Basic events L and K exist because of the rotation movement of the bond arm, as shown in Fig. 8. If the rotation movement is replaced by linear movement, as shown in Fig. 9, the root cause for die rotation during stage II may be eliminated. As a result, the branch labeled “Stage II” in Fig. 4 can be eliminated. The reliability of the bonding process should be improved.

The fault tree for stage I has four branches (Fig. 7). The intermediate event “die is not centered” appears in three of the four branches. Simplification of this fault tree should increase process reliability. If the collet could be placed

Table 3
Performance comparison

	Rotation ($^\circ$)	Failure rate (%)
Before modification	3	3
After modification	2	3

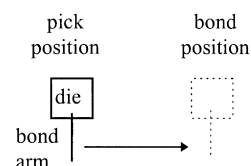


Fig. 9. Top view of the new process of stage II.

closer to the die in Fig. 5a, the movements shown in Fig. 5b and 5c can be combined together. Then, the fault tree in Fig. 7 can be reduced to three branches. The die will have a smaller chance to rotate, due to the elimination of branch 2 in Fig. 7. However, implementation of the machine design is difficult. A highly robust and high precision man-machine system is required to control the position of the collet. These suggested changes are dramatic and require the original manufacturer to implement the design change.

7. Conclusions

Unlike the theoretical discussions of the fault tree and the FMEA methods, quantitative estimates of the probabilities of basic events are often unavailable in practical situations. The qualitative approach presented in this paper should provide a good example for creatively applying reliability engineering principles in practical control engineering problem solving.

The structured fault tree and FMEA concepts were used in this case study to improve the reliability of the die bonding process. The bonding process was decomposed into three stages. The events that may contribute to die rotation were identified in each stage based on the physical laws governing the motions in the process. A qualitative evaluation method was developed, based on the unique features of the process. The sequence of the motions and the occurrence frequency of the basic events in the fault tree were used to identify critical events for further analysis. Five critical events were selected for detailed analysis and experimental studies were conducted on these events. After the analysis

and experiments, modifications were made to improve the PR algorithm and the WT system. The modified process achieved a more than 30% reduction of die rotation. To further improve the process, we suggested that the process be optimized through simplification of the structured fault tree. We believe that the proposed process modification will result in a better bonding process with a higher reliability.

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