Review of Various Curing Processes and Techniques of Printed Circuit Board (PCB) and Introduction of New Innovative Thermal Curing Technique

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ABSTRACT

This paper examines the history of curing methods of Printed Circuit Boards (PCBs), especially, the thermal-based curing method with its different curing process techniques. In addition, highlighting its importance, hence, an incomplete curing process can lead to delamination, cracking, or other failures, which render the PCB useless. Moreover, various techniques used in the thermal-based curing method with their advantages will be explained. Also, the limitations of each technique will be demonstrated, such as, long curing times, uneven temperature distribution, high energy consumption, and absence of the knowledge-base of different PCBs, like board volume, heating capacity, and electronic elements. Furthermore, factors that affect the thermal-based curing method like type of material used, humidity, temperature, and time duration will be presented. So, each factor must be carefully controlled to ensure that the curing process is effective and consistent. In addition, a new innovative thermal-based curing approach will be introduced to overcome these limitations by using Artificial Intelligence (AI) techniques for the indirect prediction of temperature on PCBs. The proposed approach involves the use of new proper control based on AI technique to obtain an advanced control technique to control the heating process of PCBs during the curing process. This new approach will be developed during an ongoing research and development project.

INTRODUCTION

The curing process has become an integral part of PCBs (Printed Circuit Boards) manufacturing, ensuring that the PCB material is properly cured, resulting in high-quality, reliable, and long-lasting products. The process has evolved over time, with various techniques developed and refined to meet the ever-increasing demands of the electronics industry.

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The curing process in PCB manufacturing is the process of polymerizing (hardening) various materials using a heat source [1]. It has evolved significantly over time to meet the changing needs of the electronics industry. In the early days of PCB manufacturing, the curing process was not well-defined in terms of its steps, temperatures, and techniques. Manufacturers used various techniques, such as air drying or baking the PCB material, to harden the epoxy or resin. These methods were often inconsistent and unreliable, and the resulting PCBs were not very durable [1]. In the 1960s, thermal curing was introduced as a more reliable and consistent method of curing PCBs, when epoxy resins were first used as the substrate material [2]. This involved heating the PCB material to a specific temperature for a set duration of time in a controlled oven [1] [3]. In the following decades, advancements in technology led to the development of new curing techniques. For example, ultraviolet (UV) curing was introduced in the 1980s, which involved using UV light to cure the epoxy or resin on PCBs [4]. Over time, the curing process has become a critical step in PCB manufacturing for several reasons. These reasons will be mentioned later. The curing process has come a long way since its early days, and it continues to evolve as new materials and technologies are developed. Ongoing research and development are needed to improve the curing process and meet the ever-increasing demands of the electronics industry.

The curing process is a critical step in the manufacturing of PCBs, and it is very important for several reasons. The first of these reasons is the increasing complexity of PCBs. As PCBs have become more complex, with more layers and smaller components, it has become increasingly important to ensure that the epoxy or resin used in the PCB material is fully cured. Second, higher reliability requirements; many applications that use PCBs require high reliability and long lifetime, such as aerospace, medical, and military applications [5] [6] [7]. Third, industry standards and regulations; the electronics industry is heavily regulated, and PCB manufacturers must meet a variety of industry standards and regulations, such as the RoHS (Restriction of Hazardous Substances) directive [5]. Fourth, cost-effectiveness; proper curing can help reduce manufacturing costs in the long run by increasing lifespan of PCBs, which reduces the need for repairs or replacements. This can be particularly very important for high-volume manufacturing applications. Fifth, ensuring mechanical and electrical properties, the curing process is necessary to ensure that the epoxy or resin used in the PCB material is fully cured and provides the necessary mechanical and electrical properties for the finished product. Here, the curing affects the mechanical properties of the PCB material by creating cross-links between the resin molecules. These cross-links provide strength and stability to the material, and increase adhesion between the layers of the PCB material, making it more resistant to cracking, delamination, and other forms of mechanical stress [8]. On the other hand, the electrical properties of the PCB material are also affected by the curing process. The cured resin creates a continuous insulating layer between the conductive traces on the board, which prevents unintended electrical connections or short circuits [5] [9]. Additionally, curing can improve the dielectric constant and loss tangent of the PCB material, which affects the signal integrity and performance of the board [10]. Overall, proper curing ensures that the PCB is reliable, durable, and performs as expected, while inadequate curing can lead to poor performance or even failure over time.

The focus of this work is about the curing process of PCBs for coating and dispens-

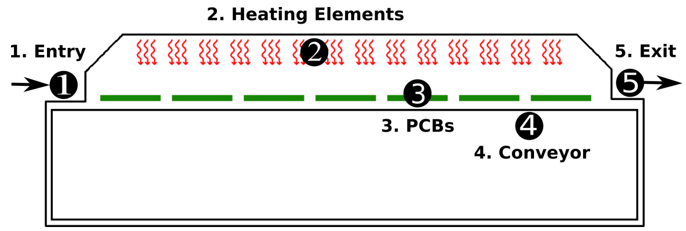

Figure 1. Horizontal oven structure

ing applications, and also its thermal method techniques, where the thermal method is the most commonly used in PCB manufacturing. This process and techniques will be briefly explained, including; examining the history of the curing process, highlighting its importance, factors affecting the thermal method, and illustrating the principle, as well as, the advantages, and the limitations of each thermal-based technique. As a result, a new innovative thermal-based curing technique will be introduced.

STATE-OF-THE-ART OF THERMAL-BASED CURING TECHNIQUES

The thermal-based method is the most commonly used in the curing process, which involves heating the PCB material to a specific temperature for a set period of time. This process activates the chemical reaction that causes the epoxy, resin, or coating material to harden, which forms a strong and stable material. The temperature and duration of the heating cycle depend on the PCB curing material being used. In this section, a brief overview at how international leading state-of-the-art competitor ovens deal with the PCBs curing process, with indication of characteristic technical data.

Inline Thermal-based Horizontal Curing Oven

This type of oven is the most traditional model used for PCB curing processes. Here, PCBs are fed into the curing oven one by one, after the main process (Coating, Dispensing, etc.) (Figure 1) [11]. Therefore, a bottleneck could be raised in the whole production line, since the curing process generally takes more time than the main process. Specifically, it is essential to either decrease the productivity of the main process machine and synchronize it with the curing process speed, or expand the capacity of the curing oven to prevent any congestion between the two machines. Furthermore, manufacturers face the option of accepting reduced productivity or making additional investments to accommodate a correspondingly larger oven with the necessary installation space.

Inline Thermal-based Vertical Curing Oven

This type of curing oven is relatively new compared to the previous oven. It is a continuous oven in vertical format, also placed after the main process machine. A horizontal conveyor transports the coated PCBs into the oven. Afterward, the PCBs are conveyed from a horizontal line onto rails inside the oven [12]. Hence, the PCBs are cured in upward and upward-downward flow (Figure 2). The oven has significant ad-

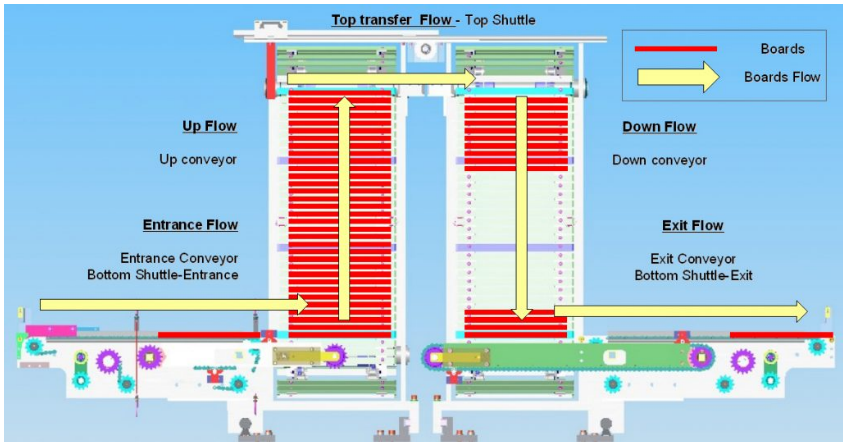

Figure 2. Vertical oven structure [12]

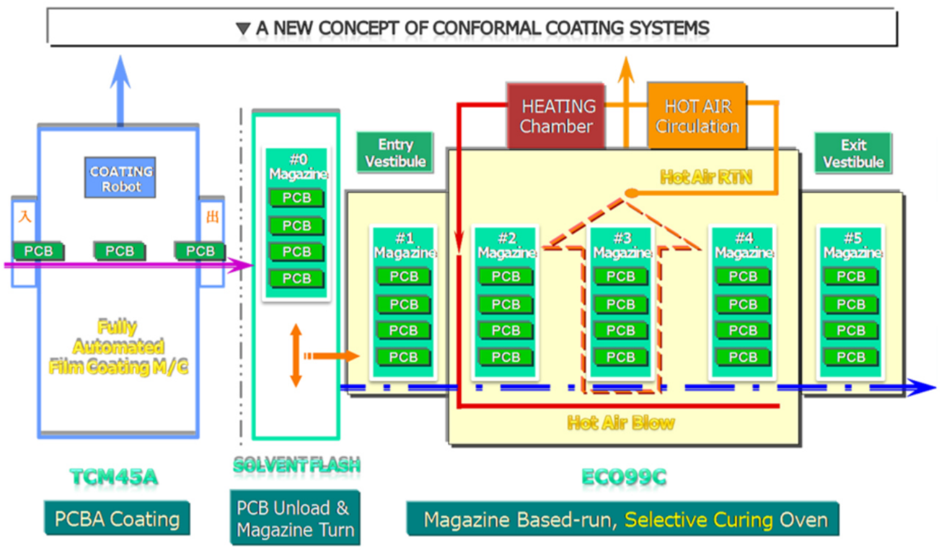

Figure 3. Magazine-based oven structure [13]

vantages compared to traditional horizontal ovens, such as, compact structure, which requires shorter length, higher productivity of related production lines, and lower energy consumption. Distinctly, a vertical inline curing oven improves the overall efficiency of production.

Magazine-based Curing Oven

This type of oven represents the most modern type of curing oven. Here, the PCBs are buffered in a magazine, where the entire magazine is inserted into the oven (Figure 3), then it moves to the exit at a constant speed through the heating chambers over a chain conveyor. The oven has many major advantages, such as, suitability, and high throughput for mass production lines, reduction of energy consumption, and short length required for installation [13].

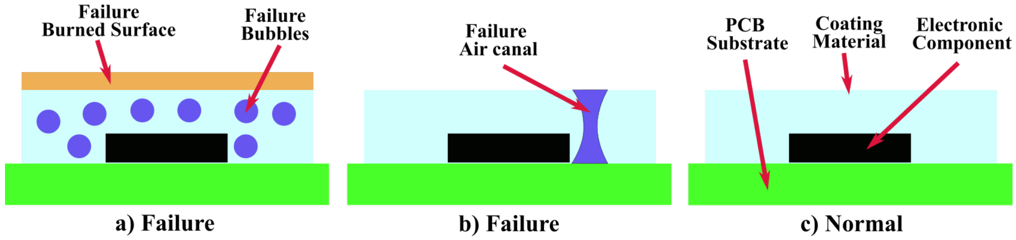

Figure 4. Failures of coating curing process

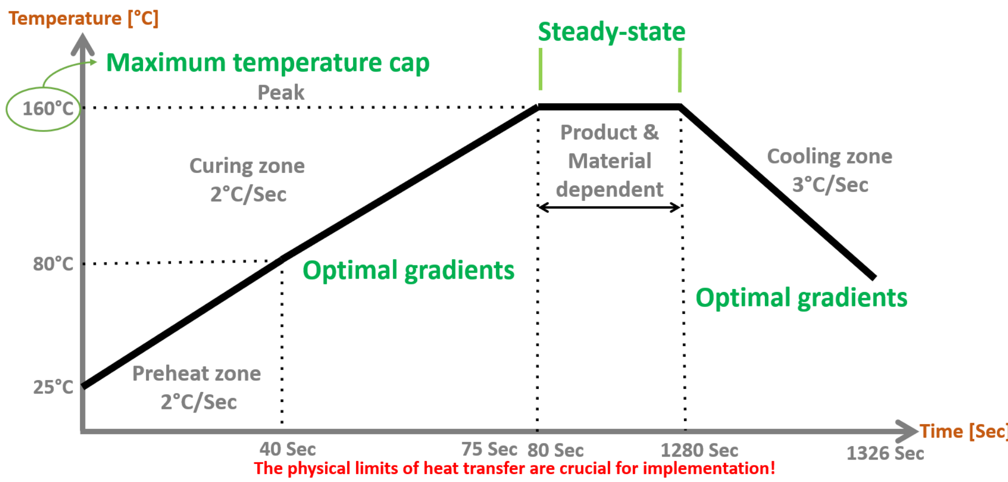

Figure 5. Condition monitoring of curing process temperature profile

AFFECTING FACTORS OF THE THERMAL-BASED CURING PROCESS

There are several factors that can affect the curing process of PCB manufacturing. The first factor is material type; the type of PCB substrate material used, and the electronic components on the PCB can have a significant impact on the curing process, as different materials require different curing temperatures and times. Second, the temperature used during the curing process is critical, where too low temperature can lead to an incomplete curing due to the poor heating of the PCB substrate as shown in figure 4 (middle). While too high temperatures can cause degradation or even burning of the PCB materials, and components, or delamination of PCB layers as illustrated in figure 4 (left) [14]. The temperature must be carefully monitored and controlled to achieve the desired results. Third, the time duration of the curing process is also crucial. Here, too short heating time can result in incomplete curing, while too long heating time can cause degradation or over-curing of the PCB material, as well, can lead to damaging electronic components. The time must be carefully optimized to achieve the desired results. Last, the humidity level in the curing environment can also affect the curing process, since high humidity can slow down the curing process and leading to change the physical and/or chemical transformations of the material [15]. Each of these factors must be carefully monitored, controlled, and optimized to ensure that the curing process is effective and consistent, resulting in a high-quality PCB products.

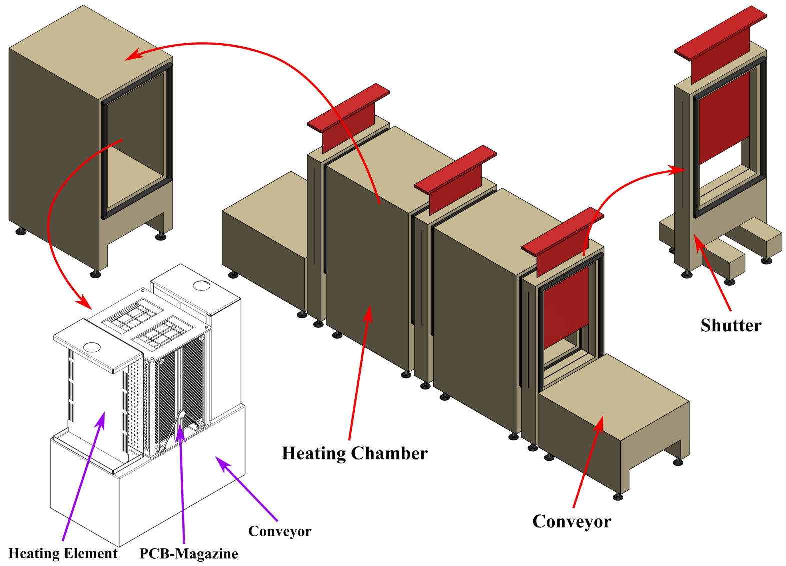

Figure 6. Modular magazine convection oven concept

INTRODUCTION OF NEW INNOVATIVE THERMAL CURING TECHNIQUE

Although each of the previous systems has many good aspects, there is an insist need for a new system that provides additional advanced features, especially for (high mix - low volume) production. Such as, decoupling the main process from the curing process, where the main process continue working despite any malfunction could occur in the curing oven. In addition, temperature traceability is required of individual PCBs for quality control. Also, reduce energy consumption, which is a critical factor in manufacturing. Moreover, less parameters tuning is necessary to reduce the need of tuning experience, which can lead to decrease the preparation time of curing process for different PCB products. Furthermore, short length of structure is desirable to reduce installation occupied area. Last, suitability for production of many different products with low quantity of each product (high mix - low volume), and production of a few different products with high quantity of each product (low mix - high volume). Due to these insist features and the factors that affect the curing process, a brief description will be introduced in this section of the development of a modern innovative thermal-based curing oven called modular magazine convection oven.

The new oven consists of a PCB-magazine, associated conveyor, heating elements, shutters, and a control unit as shown in figure 6. Here, after the main process, a set of PCBs will be stacked in a magazine. After a while, the charged magazine will be driven into the curing chamber in order to cure the set of PCBs simultaneously. The curing is a convection process, in which the PCBs are cured using hot-air circulation through heating element units. A specific temperature profile during the curing process should be ensured for each PCB in the magazine, as illustrated in figure 5. Therefore, an online temperature measurement should be realized. Since it is not possible to perform a direct temperature measurement of the individual PCBs, a machine learning (ML) system in terms of regression task, as temperature prediction tool will be used to obtain online prediction of temperatures of the individual PCBs. As well, this tool should give

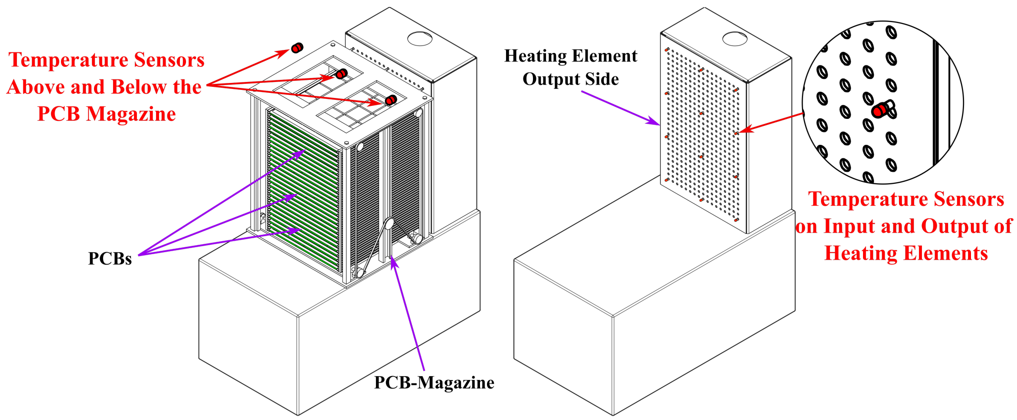

Figure 7. Sensors placement

precise temperature profiling in order to avoid the curing faults that can occur due to overheating. These obtained temperatures will be fed to an advanced control system in order to control the thermal flow within the heating chamber. The suggested AI-based temperature prediction tool will be trained by using the signal-based model simulation of the modular magazine convection oven.

The signal-based model simulation will use the temperature, which will be measured on different products of PCBs and the heating chamber environment under different situations, including the temperature of input and output of heated air flow with all oven parameters. Since the oven system is a complex and non-linear plant due to the dynamics of the temperature, and due to the need for tuning experience and difficulty in achieving a mathematical model, an advanced control system using a neuro-fuzzy controller will be used. This provides a chance to solve tuning issues and the complexity of complex logic designs [16].

The placement of sensors in various locations inside the oven, as well as at the points where hot air enters and exits (Figure 7), aims to determine the amount of heat absorbed by both the oven walls and the PCBs. Theoretically, the temperature of the output air flow will be a certain amount lower than the input air flow. This lost heat is gained by the PCBs and the walls of the oven, assuming minimal heat leakage. Therefore, a relationship can be established between the PCBs temperature and the different sensor readings. This relationship can be determined using a signal-based model with an appropriate prediction method without the need for complex mathematical model derivation.

This oven technology offers many economical aspects. First, enhancing the curing result because of its advanced control system. Second, productivity aspects, where it provides an acceleration of the curing process by avoidance of unnecessary time delay. Third, geometrical aspects. Due to its compact size, the overall system requires less occupied space for installation. Fourth, energy aspects. Here, more efficient use of energy is achieved by separating the heating chambers with shutters, which prevent the heating from flowing outside to other chambers. In addition, the use of the advanced control system gives more accurate heat control to achieve the target temperatures. Fifth, scalability aspects. Due to the modular architectural design of the oven, which is divided into two main elements (heating chamber, shutter), the installation could be established as much as required, where the smallest size of the oven contains one heating chamber and two shutters. Hence, the elements can be combined based on the customer requirement, or production volume. This gives the system the ability to be used in the production of (high mix - low volume), and in the production of (low mix - high volume). Last, decoupling of the main process from the curing process. Here, there is no need to wait until the curing process is finished to complete the job of the main process, where the PCBs are stacked in the magazine after the main process.

REFERENCES

1. Pham, H. Q. and M. J. Marks. 2005. *Epoxy Resins*, John Wiley & Sons, Ltd, ISBN 9783527306732.
2. PCBcart. 2005, “Development History of PCB Fabrication Technology,” .
3. Tifkitsis, K., A. Winistoerfer, and A. Skordos. 2023. “Online optimisation and active control of the cure process of thick composite laminates,” *Journal of Manufacturing Processes*, 87:221–230, ISSN 1526-6125.
4. Veilly, A. 2005, “The different conformal coating curing techniques. Focus on UV and UV LED curing processes.” .
5. Yun Chen, D. and M. Osterman. 2016. “Reliability of conformal coated surface mount packages,” in *2016 IEEE Accelerated Stress Testing & Reliability Conference (ASTR)*, pp. 1–5, doi:10.1109/ASTR.2016.7762293.
6. Abbas, A.-A. F., C. M. Greene, K. Srihari, D. Santos, and G. Pandiarajan. 2019. “Impact of Conformal Coating Material on the Long-Term Reliability of Ball Grid Array Solder Joints,” *Procedia Manufacturing*, 38:1138–1142, ISSN 2351-9789.
7. Peng, Y., X. Qi, and C. Chrisafides. 2005. “The influence of curing systems on epoxide-based PCB laminate performance,” *Circuit World*, 31(4):14–20, ISSN 0305-6120.
8. Zhang, J., T. Li, H. Wang, Y. Liu, and Y. Yu. 2014. “Monitoring extent of curing and thermal–mechanical property study of printed circuit board substrates,” *Microelectronics Reliability*, 54(3):619–628, ISSN 0026-2714.
9. Canal Marques, A., J.-M. Cabrera, and C. de Fraga Malfatti. 2013. “Printed circuit boards: A review on the perspective of sustainability,” *Journal of Environmental Management*, 131:298–306, ISSN 0301-4797.
10. Ciszewski, P., M. Sochacki, W. Steplewski, M. Kościelski, A. Araźna, and K. Janeczek. 2022. “A comparative analysis of printed circuit drying methods for the reliability of assembly process,” *Microelectronics Reliability*, 129:114478, ISSN 0026-2714.
11. Nordson-Asymtic. 2020, “ASYMTEK IR/Convection Oven TC Series,” .
12. Heller-Industries. 2018, “Heller VCO 755 In-line, Continuous Cure, Vertical Format Mini Curing Oven,” .
13. TTnS-Group. 2019, “Magazine-based Curing Oven,” .
14. Froš, D., P. Veselý, J. Zemen, and K. Dušek. 2022. “Latent heat induced deformation of PCB substrate: Measurement and simulation,” *Case Studies in Thermal Engineering*, 36:102173, ISSN 2214-157X.
15. Lettieri, M. and M. Frigione. 2012. “Effects of humid environment on thermal and mechanical properties of a cold-curing structural epoxy adhesive,” *Construction and Building Materials*, 30:753–760, ISSN 0950-0618.
16. Nguyen, T.-L., S. Kavuri, and M. Lee. 2019. “A multimodal convolutional neuro-fuzzy network for emotion understanding of movie clips,” *Neural Networks*, 118:208–219, ISSN 0893-6080.