The study of typical failure modes and failure mechanism of polymer materials

Huanxiang Xu, Yanhuang Tang, Zilian Liu, Yingying Cai and Youliang Wang
Reliability Research and Analysis Center, The Fifth Electronics Research Institute of Ministry of Industry and Information Technology, Guangzhou 510610

Abstract. Polymer materials are widely used because of their unique properties such as light, easy processing, various performance and so on. However, due to the structural characteristics of polymer materials, some conditions such as light, heat, solvents and so on will cause polymer materials failure. In this paper, the typical failure modes and failure mechanism of polymer materials such as cracking, discoloration, bulging, precipitates and so on are analyzed and discussed.

1 Introduction
Polymer materials and steel, wood, cement together as the four basic materials in the national economy, are considered to be new materials to promote the development of social productivity. Polymer materials are widely used in chemical industry, electronics, information technology, aerospace and other industries because of their unique properties such as light, easy processing, various performance and so on. In the 1980s, the output of plastic was more than steel in volume. With the improvement of the structure, function and performance of the polymer materials, "Replacing steel with plastic " has become the development trend of polymer manufacturing [1]. Polymer materials are based on organic covalent bond, under the condition of the electrochemical corrosion of metal, the corrosion of polymer materials will not occur, but a serious aging failure behavior will occur. During use, by the combined effect of heat, oxygen, water, light, microorganism, chemical medium and other environmental factors, the chemical composition and structure of polymer materials will undergo a series of changes. So the physical properties will change accordingly, such as hard, brittle, discolored, loss of strength etc., these changes and phenomena are called polymer corrosion (aging) [2]. The harm caused by aging is very serious, often lead to premature failure of the material.

The failure of the material with time is generally divided into three stages, its typical failure curve is similar to a bath, called the bathtub curve [11]. The three failure stages are respectively early failure period, accidental failure period and loss failure period. The early failure is mainly caused by the defects in the design and manufacture such as improper design, improper material selection, processing defects, improper installation, improper use and so on. To study the cause of early failure period of polymer materials, and clarify its failure modes and failure mechanism, that can provide the basis to improve product quality and improve product life.

Based on the analysis of several typical cases, this paper analyzes the typical failure modes and the corresponding failure mechanism of polymer materials by means of various failure analysis methods, and find the root cause of the failure. This is of significance for the improving product quality and improving product life.
Polymers are a kind of material which is based on polymer compound as the matrix and together with other additives. Polymer materials are classified into plastic, rubber, fiber, polymer adhesive, polymer coating and polymer matrix composites according to their characteristics. Therefore, there are many kinds of polymer materials, each material has its own advantages and disadvantages due to its own structural characteristics. If used improperly, the material will fail. Typical failure modes of polymer materials are cracking, discoloration, bulging, precipitation and so on. Each failure mode corresponds to different failure mechanisms, even if the same failure mode has several failure mechanisms. The failure mechanism is analyzed in detail below for different failure modes.

2.1 Cracking
There are three main causes of polymer product cracking. The first kind of cracking is caused by insufficient bearing capacity, which is mainly due to improper material selection. For instance, the strength of the selected material is too low, unable to afford the actual force requirements, resulting in product cracking; The second is due to the addition of too much filler to polymer material, resulting in product flexibility, elongation and so on are low, brittle fracture occurs during the service of the product. The third is a kind of cracking which often happens but is often ignored, that is, stress corrosion cracking. Stress corrosion cracking is the result of a combination of stress and chemistry. The main process is that small molecule solvents penetrate into the polymer, when the solvent and the polymer have a high affinity, the solvation will take place between the solvents and macromolecules on the surface layer of materials, and further penetrate into the macromolecule under the action of thermal movement. Small molecule solvent penetrated will weaken the force between chain segments, increase spacing between macromolecules and eventually make the polymer swelling. If the affinity between macromolecules and solvents is strong, the swelling can be proceed until the macromolecules dissolve, finally, the mechanical properties of polymer material are reduced, and cracks occur.

Figure 1-(a) is a new fuse-holder. Figure 1-(b) is a cracked fuse-holder used for a period of time. To prevent the nut from loosening, the 704 silicone rubber was applied to the nut of the fuse-holder. After using for a period of time the fuse-holder cracked. Figure 2 shows that the black plastic on the fuse-holder is polycarbonate(PC). Polycarbonate is an excellent engineering plastic and has the advantages of high impact strength, heat resistance, transparency, excellent dielectric performance and so on, but the poor solvent resistance, especially benzene homologues and halohydrocarbon, and is prone to stress cracking in solvent environments [7, 9, 10]. After a series of analysis and verification, the reason for cracking of the fuse-holder in this case is that the solvent especially halohydrocarbon (see table 1) in 704 silicone rubber has eroded the base polycarbonate, and this results in the decrease of the inter-molecular force and the decrease of mechanical properties of the base material of the fuse-holder, finally the fuse-holder cracks in the stress area.

Figure 1: The appearance of the fuse-holder
2.2 Discoloration

The discoloration of polymer products is also a failure phenomenon often encountered. There are two main reasons for discoloration. The first discoloration is mainly caused by aging. It usually occurs in transparent, translucent, and white products. The products usually turn yellow. The main reason is that the structure of macromolecular has been changed due to the long-term effect of light and heat. The reason for yellowing is that polymer materials produce chromophore groups under the action of light and heat [6]. When this phenomenon occurs, accompanied by changes in the apparent properties of materials such as sticky, cracked, brittle and so on, and changes in physical and mechanical properties such as molecular weight and molecular weight distribution, strength and other changes.

The second discoloration is mainly caused by external pollution. This discoloration is usually due to the colored substance released by the materials contacted with polymer products penetrating into the polymer products, resulting in discoloration of polymer products. A fan is shown in Figure 3 and the back cover of it turns yellow during storage. By observation and analysis, only the plastic in contact with the black dustproof net turn yellow. After the plastic on the yellow position was soaked in solvent, the soaking solution turns yellow and the color of plastic on the yellow position reverts to its original color. The soaking solution of the yellow plastic and the black dustproof net are both detected the similar ingredients as shown in Table 2. Most of Table 2 are benzene homologues, and 2% acetophenone. Acetophenone is a light yellow oily liquid at room temperature [3], which can be oxidized to produce benzoic acid, produce ethyl benzene when reduced. Acetophenone can be used as plasticizers in plastics [12]. The ethyl benzene in Table 2 may be the reducing product of acetophenone. So, the yellowing of the back cover of the fan is caused by the contamination of the plasticizer acetophenone in the black dust proof net.

**Figure 2:** The FT-IR spectrum of the black plastic on the fuse-holder and polycarbonate

**Table 1.** The test results of volatile gas of 704 silicone rubber

| Serial No. | Main components     | Relative content (wt%) |
|------------|---------------------|------------------------|
| 1          | Alcohol             | 10.22                  |
| 2          | Dichloromethane     | 5.53                   |
| 3          | Diethylamine        | 0.26                   |
| 4          | Trichloromethane    | 0.37                   |
| 5          | Siloxane            | 83.62                  |

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Table 2. The test results of soaking solution of the plastic on the yellow position

| Serial No. | Main components          | Test results | Relative content (wt%) |
|-----------|--------------------------|--------------|------------------------|
| 1         | Ethyl benzene            |              | 44.17                  |
| 2         | Xylene                   |              | 43.27                  |
| 3         | Cumene                   |              | 0.50                   |
| 4         | Propylbenzene            |              | 0.25                   |
| 5         | Methyl ethylbenzene      |              | 0.41                   |
| 6         | Methyl benzyl alcohol    |              | 0.31                   |
| 7         | Acetophenone             |              | 2.09                   |
| 8         | Methyl benzaldehyde      |              | 0.99                   |
| 9         | Long chain alkanes       |              | 1.82                   |
| 10        | Silicone                 |              | 6.19                   |

2.3 Bulging

Bulging is also a common failure phenomenon of polymer material. Bulging often occurs when the polymer material exposes to a high temperature, for example, if some high hygroscopic material are not dried before processing, during the processing, the release of water vapor leads to the appearance of bulges on the surface of the molded parts. In addition, even if the polymer parts have been formed, if the polymer parts have high hygroscopicity, and after reflow soldering, the surface of the polymer parts is also prone to bulge phenomenon.

Figure 4(a) is a nylon connector. After reflow soldering (reflow peak temperature is 235℃), bulging occurs on the surface of the connector. Figure 4(b) is the section of the bulging connector. It can be seen from the slice morphology that there are many holes inside the connector. By analysis and verification, bulging is because the nylon material of the failure connector has high water absorption and reaching to 3% (shown in Figure 5), during reflow soldering, the moisture inside the connector is released to produce water vapor that spills over to the surface, leading to the connector bulging.
2.4 Precipitates

The separating out of liquid or solid on the surface of polymer materials is another frequent failure phenomenon. Precipitates are usually additives that are added to the polymer during processing. Separating out of additives is a common quality problem of polymer materials, it usually occurs when polymer parts undergo a harsh environment (such as high temperature and high humidity). There are three main forms of separating out: sweating, spraying frost and precipitating crystalline substance[8]. The reason for its precipitation is generally improper formula design and improper operation.

Figure 6 is a polycarbonate plastic cover. Figure 6(a) is a failure sample. There is yellowish liquid on the cover after a period of use. Figure 6(b) is a new sample. As shown in Figure 6 (a) and Figure 6 (b), the cover should be colorless and transparent, but the surface of failure cover is covered with yellowish liquid after using a period of use. By analysis and verification, the yellowish liquid is triphenyl phosphate. Triphenyl phosphate is white, tasteless crystalline powder at room temperature[4], but its melting point is low and after melting it is colorless to yellowish transparent liquid. It is mainly used as flame retardant for cables, wires and engineering plastics[5]. So the triphenyl phosphate on the surface of failure cover is a flame retardant additive in the plastic cover.

Figure 5: The TGA curves of the failure connector before and after soaking

Figure 4: The appearance of the bulging sample

Figure 6: the appearance of the plastic cover
2.5 Production process defects

The failure of polymer materials often occurs in the process of production. For example, a series of failures caused by improper setting of forming conditions during processing, such as weld line, flow mark, lack of material, flying edge and so on. The failure defects during processing can be avoided through the improvement of mold design and molding process conditions. There are also some defects in the coating process such as orange peel, sagging, coating cracks, poor adhesion and so on. These defects can be avoided by improving the surface of sprayed parts, proportion of the coating, spraying process.

3 Conclusion

The failure of polymer materials not only affects the appearance of polymer products, but also affects the properties of polymers such as physical properties, mechanical properties, electrical properties, etc., and even causes serious quality accidents. It is of great significance to study the failure modes of polymer materials and make their failure mechanism clear and find the root cause of the failure. Therefore, improving the reliability of polymer materials is a systematic project, which depends on the early selection and design of materials, product manufacturing process and the latter application environment. In the design, designer should take full account of the characteristics of product, choose the right materials according to the application environment to reduce the failure of polymer products and reduce economic losses.

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