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DOI
10.1109/ACCESS.2019.2900361

Publication date
2019

Document Version
Final published version

Published in
IEEE Access

Citation (APA)
Cai, M., Liang, Y., Yun, M., Chen, X.-Y., Yan, H., Yu, Z., Yang, D., & Zhang, G. (2019). Effects of Thermal Reflowing Stress on Mechanical Properties of Novel SMT-SREKs. *IEEE Access*, *7*, 27106-27114. Article 8648339. https://doi.org/10.1109/ACCESS.2019.2900361

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 16, 2019, accepted February 12, 2019, date of publication February 21, 2019, date of current version March 13, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2900361

Effects of Thermal Reflowing Stress on Mechanical Properties of Novel SMT-SREKs

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This work was supported in part by the National Natural Science Foundation of China under Grant 61865004 and Grant 21805055, in part by the Natural Science Foundation of Guangxi Province under Grant 2018GXNSFAA138033 and Grant 2017GXNSFDA198006, in part by the Innovation-Driven Development Project of Guangxi Province under Grant 2018AA18029 and Grant AA17204063, in part by the Guangxi Key Laboratory of Manufacturing Systems Foundation under Grant 17-259-05-003Z, and in part by the Program of Guilin Science Research and Technology Development under Grant 2016010501-3 and Grant 20170113-11.

ABSTRACT A novel silicone rubber elastic key (SREK) is proposed in this paper for surface mounting technology (SMT) applications. Effects of thermal reflowing stress on the mechanical properties of SMT-SREKs are investigated. The manufactured SMT-SREKs, which underwent various reflowing conditions in advance, are subjected to pressing force and fatigue pressing tests. Fatigue lifetime projection model and its predicted error are then assessed systematically. The thermal degradation of silicone rubber materials is illustrated through the dynamic mechanical analysis and the Fourier transform infrared spectroscopy experiments. The mechanical finite element modeling is also conducted to simulate the pressing process. The results show that the pressing force and tactility of the SMT-SREKs are strongly affected by the reflowing condition, which contributes to the degradation of the silicone rubber materials. During the fatigue pressing test, the change rate of tactility increases with the reflowing peak temperature (T_p) and is accelerated by the repeated reflowing process. Moreover, a linear model can precisely project the tactility before the fatigue pressing number of $2.0E+6$ times, and the impact rate of T_p on tactility with the increasing fatigue pressing number can be predicted effectively by using a logarithm model.

INDEX TERMS Silicone rubber elastic key (SREK), surface mounting technology (SMT), mechanical property, degradation, fatigue lifetime, modeling.

I. INTRODUCTION

Silicone rubber is mainly composed of siloxane segments containing methyl and a small amount of vinyl; this material has a complex structure created through crosslinking reactions [1], [2]. Given the low cost, good mechanical properties, and stable electric insulation of silicone rubber material, it has been widely used in the electronic industry [3]–[6]. Conductive monomer connectors manufactured with silicone rubber composites are commonly referred to as silicone rubber elastic keys (SREKs). Most electronic products, such as toys, telephones, mobile devices, computer keyboards, electronic controllers, and vehicle control systems, need functional SREKs. However, SREKs have several disadvantages. First, existing SREKs are generally non-standard parts. Each electronic product needs a pair of SREK molds. Completely new mold designs and manufacturing processes are needed because the requirements of individual products on the shape and size of SREKs vary and a unified product standard is lacking. Second, positioning and assembling in the assembly process of actual SREK applications are conducted artificially, indicating low production efficiency.

In microelectronic packaging, surface mounting components emerged along with surface mounting technology (SMT) in the 1980s and brought about a technological revolution in electronic device applications. The applications of surface mounting components have many advantages. For example, the surface utilization percentage of printed circuit board (PCB) increases, automatic production can be performed, and the efficiency of assembly production can

The associate editor coordinating the review of this manuscript and approving it for publication was Dong Wang.

be greatly improved. To address the abovementioned problems of existing SREKs, a novel type of material called SMT-SREK has been developed in recent years [7]. The novel design breaks through the forms of corresponding positioning design of traditional SREKs with positioning feet. The traditional assembly efficiency depending on the manual positioning and assembling can be effectively improved. The SMT-SREKs bring a qualitative change to traditional SREKs and their application. The main change for the applications of novel SMT-SREKs is to undergo the process of thermal reflowing as a new application form. With this change, the temperature effect on the mechanical performance of SMT-SREKs becomes a concern.

However, investigations on the temperature influence on mechanical performance and reliability assessment for SMT-SREK applications are limited. Some scholars have studied the mechanical, thermal, and aging properties of silicone rubbers for various applications [8], [9]. For example, Chandrasekar *et al.* [10] investigated the aging of silicone rubber insulation material in a high-temperature environment and found that thermal aging affects the tensile strength and storage modulus characteristics of silicone rubber materials. Chang *et al.* [11] investigated the temperature and humidity effect on the aging of silicone rubbers as sealing materials and found that aging of silicone rubbers becomes more severe with increasing temperature, mainly resulting from the chemical decomposition of cross-linker units for the connection of polysiloxane backbones and methyl groups attached to silicon atoms. Meanwhile, Zhang *et al.* [12] studied the thermal degradation and thermal stability of conductive silicone rubber filled with conductive carbon black and found that thermal degradation of conductive silicone rubber begins at approximately 350 °C and ends at approximately 600 °C. Tan *et al.* [1] investigated the time-dependent chemical and mechanical degradation of silicone rubber and found that temperature has a significant effect on the degradation (i.e., the higher the temperature, the faster the material degraded) and that chemical degradation or mechanical compressive load affects the mechanical properties. Wu *et al.* [13] investigated the aging mechanism of silicone rubber by using thermal oxidation aging test and X-ray photoelectron spectroscopy (XPS) and nuclear magnetic resonance (NMR) spectroscopy analysis. They concluded that the hardness and compression set can increase with aging of silicone rubber, and also surface roughness and aging can lead to the degradation of silicone rubber sealing performance.

Many aging problems occur in silicone rubber applications during long-term usage, which lead to changes in physical properties [14], [15]. Some researchers found that after long usage in different environments, the silicone rubber surface may crack and its tensile strength may decline [16], [17]. Furthermore, the specimen hardness, tensile strength, and elongation at break may also increase [9], [18], [19]. Zhu *et al.* [20] studied the surface degradation of unfilled high-temperature vulcanized silicone rubber resulting from creeping corona discharges under atmospheric pressure.

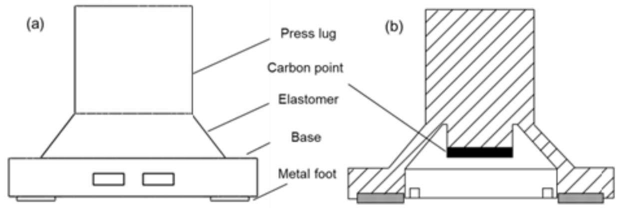

FIGURE 1. **Schematic of SMT-SREK outline (a) and cross section (b).**

They found that obvious cracks and mechanical damages caused by the corona discharge appear on the aged silicone rubber surface. Kim *et al.* [21] investigated the adhesion properties and thermal degradation of silicone rubber by measuring the activation energy and found that adding carbon black to the silicone rubber increases the adhesion force significantly. For the novel SMT-SREKs, studies on temperature effect, fatigue, and lifetime prediction are urgently needed to guide standardization and normalization in the future.

In this work, the manufactured SMT-SREKs, subjected to different thermal reflowing conditions in advance, are subjected to pressing force and fatigue cyclic pressing tests. The fatigue lifetime of SMT-SREKs and its predicted error are evaluated, and a fatigue projection model is created from the experimental data of the fatigue cyclic pressing test. Meanwhile, dynamic mechanical analysis (DMA) and Fourier transform infrared (FTIR) spectroscopy are employed to elucidate the thermal degradation of the mechanical properties of silicone rubber materials in the reflowing process. Moreover, the effect of thermal reflowing stress on the mechanical performance of SMT-SREKs is analyzed using mechanical finite element modeling.

II. EXPERIMENTAL METHODOLOGY

A. TACTILITY OF SMT-SREKS

One type of SMT-SREK is manufactured and investigated in this work. Its structure consists of a base, conical hollow elastomer, press lug, conductive carbon point, and two symmetrical metal feet on the bottom surface of the base (Fig. 1). A metal holder is connected to the symmetrical metal feet and embedded in the base. The metal feet protrude normally 0.1 mm below the base bottom to ensure their solderability to PCB pads in the thermal reflowing process. In the manufacturing process of SMT-SREKs, the formed metal holder with two symmetrical metal feet and the carbon point are mechanically fixed on a lower mold. Then, a vulcanization process of silicone rubber paved on the formed metal holder is conducted with a hot-pressed molding. The maximum curing temperature in the hot-pressed molding is approximately 150 °C.

Generally, a weight-displacement curve, which is presented by a double-S curve (Fig. 2), can be generated in the pressing process of SREKs. The double-S curve consists of an actuation force curve and a resilience curve. The actuation force can be monitored as the displacement increases while pressure is loaded on the press lug of the SREK.

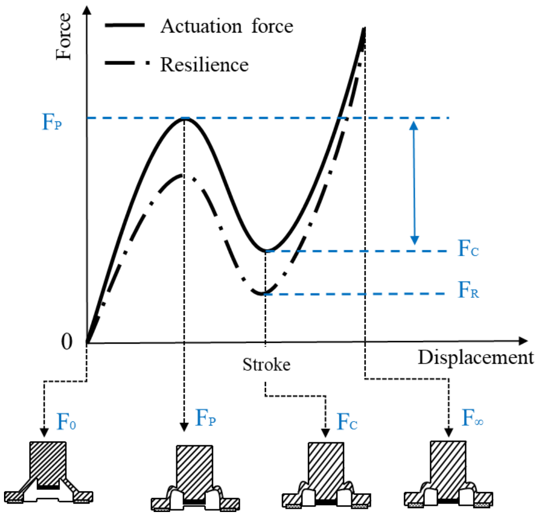

FIGURE 2. Double-S curve of weight displacement generated in pressing process of SREK.

The resilience can also be detected on the press lug as the displacement decreases while the pressure is released gradually and the SREK returns to its original shape. The shape of the double-S curve mainly depends on the elastomer and the stroke of a SREK. The tactility value (T_r) is one of the important indexes to evaluate the mechanical performance of SREKs. The peak value (F_p) and peak valley value (F_c) on the S curve are usually applied to calculate T_r with the following formula:

$$T_r = \frac{(F_p - F_c)}{F_p} \times 100\%. \tag{1}$$

Generally, when T_r is relatively large, the resilience (F_R) is very small. In the pressing process of SREK, a failure mode failing to rebound appears easily. When T_r is very small, the tactility to press the SREK becomes extremely poor. Normally, the T_r range of SREKs should be 40%–70%, and the SREK should be regarded as a failure when T_r is beyond this range. T_r is regarded as a key parameter in assessing SMT-SREK mechanical performance.

B. THERMAL REFLOWING STRESS

Compared with the manufacturing process using traditional SREKs, an additional thermal reflowing process is conducted for SMT-SREKs. Fig. 3 shows an exemplified profile of the thermal reflowing process. Normally, four phases are present in the reflowing profile, including preheating, thermal insulating, soldering, and cooling zones. In this work, the peak temperature of the reflowing profile (T_p) is regarded as a critical factor that affects the mechanical performance of SMT-SREKs (Fig. 3). Three levels of T_p in the same reflowing profile, namely, 235, 245, and 255 °C, are involved. The impact of the repeated reflowing process on the mechanical performance of SMT-SREKs is also considered. The thermal reflowing processes are implemented with a desktop reflowing furnace with an error (± 2 °C). The T_p in the soldering zone is guaranteed by a thermal monitoring sensor placed on the PCB surface.

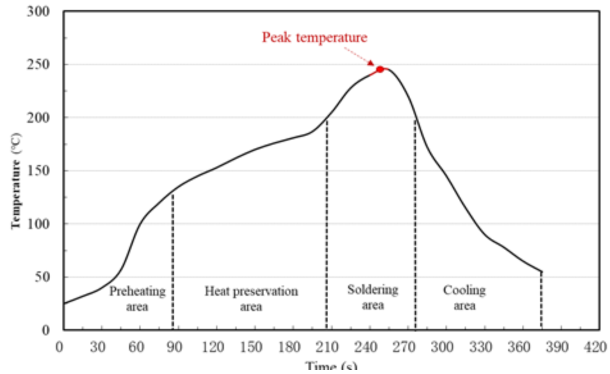

FIGURE 3. Schematic of reflowing profile in soldering process.

In this work, 20 units are involved in investigating the effect of reflowing stress on the mechanical properties of SMT-SREKs. The manufactured SMT-SREKs, subjected to three thermal reflowing conditions (namely, 235, 245, and 255 °C), are submitted to a fatigue cyclic pressing test for a maximum pressing number of 2.5E + 6 times, and the weight-displacement curves of the SMT-SREKs are monitored by the weight-displacement test for 5.0E + 5 times each. Meanwhile, the elastic performance of silicone materials treated with different reflowing profiles is analyzed with a DMA tester, and the FTIR spectra are measured to illustrate the degradation of the rubber materials.

Moreover, finite element modeling of the mechanical pressing process is also implemented with the Ansys software to demonstrate the crucial part of SREKs in practical application. The well-known hyper elastic Mooney–Rivlin model [22] is employed to match the elastic characteristics of silicone rubber materials in the SREK model. The SREK model is set with elastic modulus (2.5 MPa), Poisson's ratio (0.48), and density (1100 Kg/m^3), and the bottom face of the base is fixed on a horizontal PCB without movement to any direction. The press lug is loaded with a downward displacement, and then a weight-displacement response can be achieved at the surface of press lug.

The fatigue lifetime of the SMT-SREK and its predicted error are evaluated. A fatigue projection model is developed based on the experimental data of fatigue cyclic pressing testing.

III. RESULTS AND DISCUSSIONS

A. THERMAL DEGRADATION OF MECHANICAL PROPERTIES OF SMT-SREKS IN REFLOWING PROCESS

The manufactured SMT-SREKs are soldered on a PCB in thermal reflowing profile with T_p of 235, 245, and 255 °C (marked with reflow 235, reflow 245, and reflow 255, respectively). The pressing forces of SMT-SREKs are measured with a weight-displacement tester. The pressing force is visually a double-S curve, including a positive pressing response trace and a negative direction return response trace (Fig. 4).

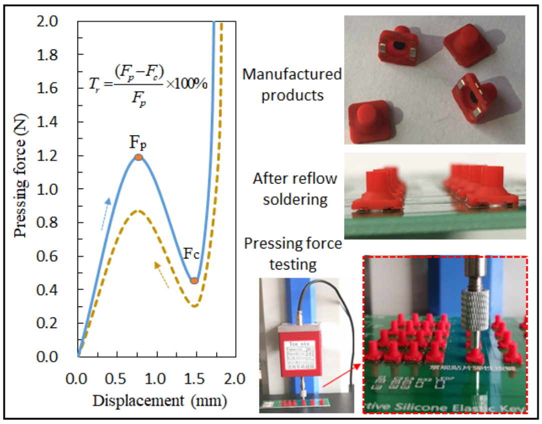

FIGURE 4. Typical pressing force curve of SMT-SREKs soldered on a PCB.

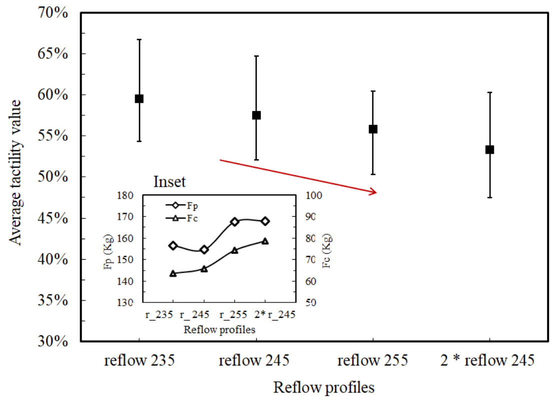

FIGURE 5. Change in average T_r with increasing T_p (inset: changes of F_p and F_c forces).

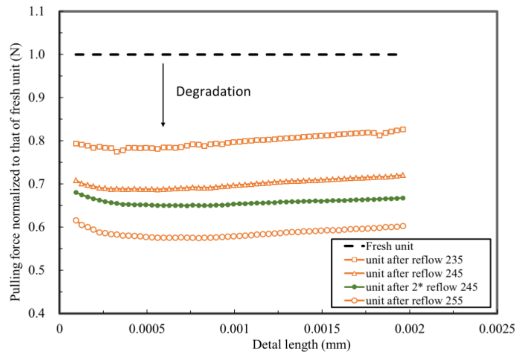

FIGURE 6. DMA test result of silicone rubber materials subjected to different reflowing conditions.

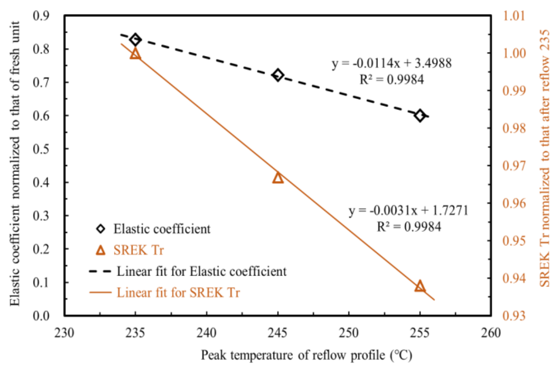

FIGURE 7. Material elastic coefficient and SREK T_r with increasing T_p.

In an actual pressing process, the pressing displacement of the press lug increases with the gradual increase of the pressing force loaded on the press lug of a SMT-SREK, and then a "yielding" phenomenon occurs on the press lug while the pressing force reaches the peak value of F_p, followed by a significant decrease until the displacement reaches the stroke of SMT-SREK. Then, the pressing force climbs sharply with the slight increase of displacement with the deformation of the press lug and carbon point. Thereafter, the pressure is released gradually and the SREK returns to its original shape. Accordingly, the force monitored on the press lug shows a returning trace and forms a closed double-S curve with the positive response trace. Tactility is known as a key index for quantifying the actual feeling of the pressing process and calculated based on the feature of the double-S curve, that is, Equation (1).

In this study, 20 units for each condition are measured. To investigate the impact of repeated soldering process on the products, one group of SMT-SREKs soldered on a PCB is exposed to two time reflowing profiles with T_p of 245 °C (marked with 2 ∗ reflow 245). T_r is calculated using equation (1). Fig. 5 presents the average T_r of SMT-SREKs that experience different reflowing profiles. The mechanical properties of silicone rubber materials are highly sensitive to the increase of subjected temperature [11], and the hardness and compression set of silicone rubber materials increase with increasing temperature [9], [13]. A similar decay phenomenon was found in SMT-SREKs subjected to the reflowing process. Notably, F_p and F_c increase with increasing T_p (inset of Fig. 5). T_r declines gradually with increasing T_p, and the double reflowing process further exacerbates this decay. Evidently, the effect of T_p on the tactility of SMT-SREKs is remarkable. DMA results show the substantial degradation of mechanical properties for silicone rubber materials in thermal reflowing stresses (Fig. 6). The pulling force of silicone rubber materials drops sharply by 20%–40% after different reflowing conditions. The elastic coefficient of silicone rubber material degrades in a similar manner as T_r with increasing T_p (Fig. 7).

The FTIR spectra illustrate further the degradation mechanisms of silicone rubber materials in different reflowing processes (Fig. 8 (a)). The broadest and strongest absorption peaks near 1010 and 1080 cm^{-1} from the stretching vibrations of cross-linkers (Si-O-Si bonds) on the backbone of silicone rubbers decrease significantly after the reflowing process (Fig. 8 (b)); a similar decline is also observed in the absorption peak at 793 cm^{-1} from the coupling of stretching vibration of Si-C and rocking vibration of $-CH_3$ (Fig. 8 (c)). A sudden chemical degradation should occur in high

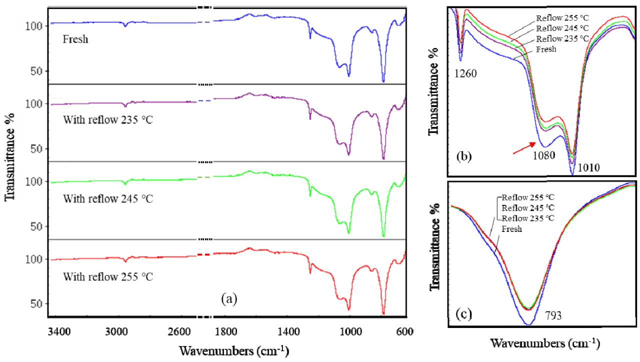

FIGURE 8. ART–FTIR spectra of silicone rubber materials before/after reflowing processes.

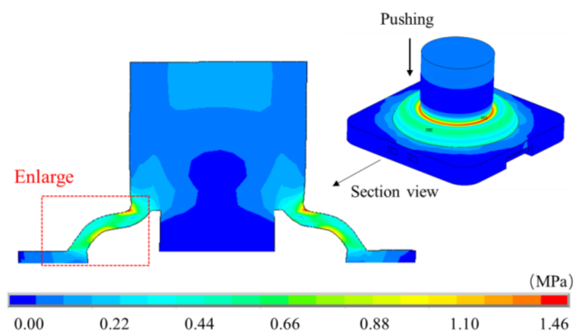

FIGURE 9. Mechanical stress distribution in pressing process.

reflowing temperature, mainly including de-crosslinking reaction at cross-linked sites of silicone rubbers and combination reaction on the rubber backbone [1], [9], [11]. Furthermore, the increasing T_p, acting as a thermal shock stress to silicone rubbers, slightly aggravates the degradation of most absorption peaks on the FTIR spectra, which results in the mechanical performance decay law of SMT-SREKs in various reflowing processes. Evidently, although the duration of the reflowing process is very short, the tactility of SMT-SREKs is affected significantly and decreases with the increase of T_p because of the chemical degradations of silicone rubber materials.

Moreover, a finite element modeling of mechanical pressing for SMT-SREKs is conducted in this work (Fig. 9). The critical part of SREKs in real cycling application is the thin elastomer. The mechanical stress distribution of SREKs is located at the circular transition of the conical hollow elastomer, where it connects to the moving lug. The stress concentration at the circular transition (point 1) sharply increases with increasing downward displacement and then reaches a stable value (Fig. 10). Impressively, the mechanical stresses at points 1 and 2 rise and then saturate without a droop until they reach the stroke, rather exhibiting a significant change from a climbing to a decreasing trend, as shown by the weight-displacement curve, because the deformed elastomer of SREKs continues to bend after the yielding moment. The deformation and stress distribution of the enlarged elastomer

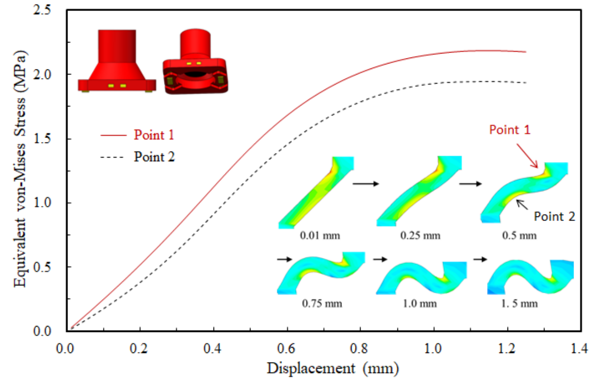

FIGURE 10. Mechanical stress concentration at circular transition connected to moving lug of SREK. (The inset shows the deformation process and stress distribution of enlarged elastomer with increasing downward displacement.)

with the increasing downward displacement are illustrated in the inset of Fig. 10.

The modeling result implies that failure modes, such as the crack or low elasticity at points 1 and 2, easily occur in fatigue testing and actual applications. The mechanical reliability of SREKs should be a significant concern, particularly when the impact of thermal reflowing process on the SREKs is involved.

B. FATIGUE LIFETIME PROJECTION OF SMT-SREKS IN FATIGUE CYCLIC PRESSING TEST

The fatigue cyclic pressing test is conducted using a pressing frequency of 60 times per minute after the SMT-SREKs are soldered on PCB pads with different reflowing conditions. The SMT-SREKs are grouped according to T_p of 235, 245, and 255 °C. Two additional groups for repeated reflowing profiles with T_p of 245 °C and 255 °C (marked with 2 $*$ reflow 245 or 255) are added for comparison. Three units for each reflowing condition are tested, and the fatigue cyclic pressing number is 2.5E+6 times for each sample. The pressing forces at the various phases of the fatigue cyclic pressing test are measured. The pressing forces at six phases in the fatigue cyclic pressing test are provided for the SMT-SREKs subjected to the reflow condition with a T_p of 235 °C (Fig. 11). The mechanical performance of SMT-SREKs exhibits an obvious decreasing trend with increasing pressing number. F_p and F_c (Figs. 12 and 13) degrade significantly in a manner of exponential law. The increasing T_p can accelerate the decay rate of SMT-SREK mechanical performance, and the temperature influence on F_c is more obvious than that on F_p. Moreover, the repeated reflowing process accelerates the decay rate before the pressing number of 1.5E + 6 times. The decay rate, to a certain extent, is decreased by the repeated process while the pressing number is over 1.5E + 6 times (Figs. 12 and 13). The yield phenomenon for the impact of repeated reflowing process on the decay rate should be attributed to the mentioned increase in the hardness and compression set of silicone rubber materials [9], [13]. The change

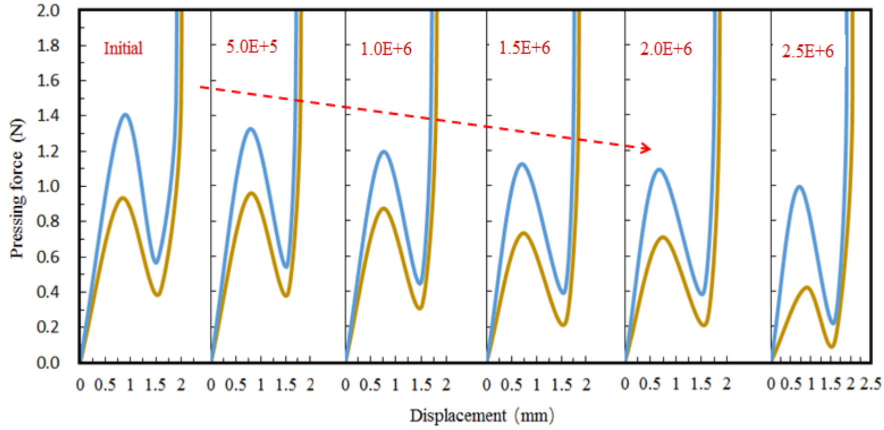

FIGURE 11. Pressing forces of SMT-SREKs at six phases in fatigue cyclic pressing test: initial, 5.0E + 5 times, 1.0E + 6 times, 1.5E + 6 times, 2.0E + 6 times, and 2.5E + 6 times.

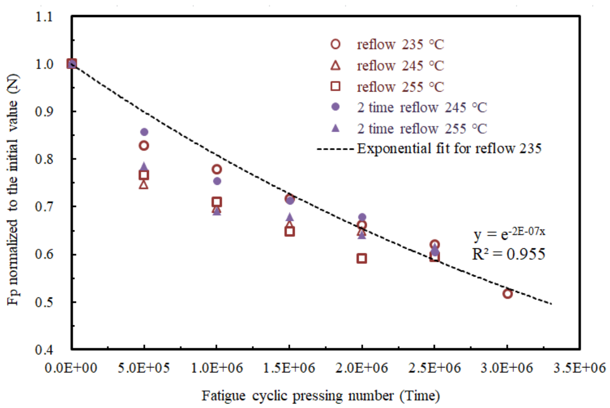

FIGURE 12. Changes in F_p during fatigue cyclic pressing test.

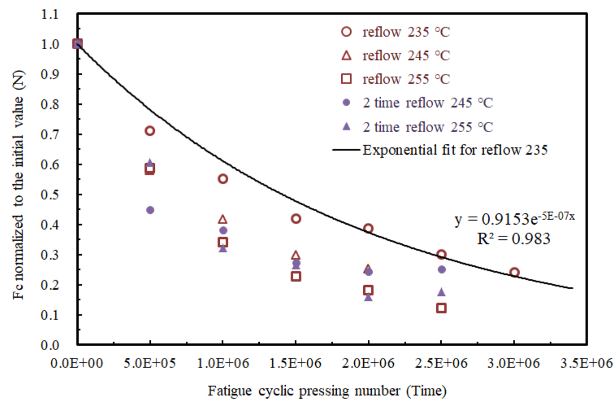

FIGURE 13. Changes in F_c during fatigue cyclic pressing test.

of T_r with increasing pressing number can further illustrate the degradation of the mechanical properties of SMT-SREKs (Fig. 14). Indeed, the increasing T_p and repeated reflowing process greatly affect the SREK tactility. Notably, the impact of the cyclic fatigue pressing number on T_r exhibits an evident increasing trend (Fig. 14), which is opposite the effect of the reflowing thermal stress level on T_r (Fig. 5). The hardness and elasticity of silicone rubber materials subjected to increasing reflowing thermal stresses increase gradually (Fig. 6), and the mechanical elastic performance of SMT-SREKs declines accordingly after the reflowing processes. By contrast, T_r increases with the fatigue pressing number (Fig. 14). The mechanical pressing process should soften the conical hollow elastomer of SMT-SREKs gradually in the fatigue test. Moreover, the T_r value depends on F_p and the difference between F_p and F_c. We believe that the changing rate of F_p is faster than that of the difference between F_p and F_c during the fatigue pressing test. Therefore, T_r shows an increasing trend with the pressing number.

During the cyclic pressing test, the change rate of T_r increases with increasing T_p and can be speeded up by the repeated reflowing process before the pressing number of approximately 1.5E + 6 times. Meanwhile, with the increase in cyclic pressing number, T_r is changed in a linear law. A linear fitted equation with a high fit goodness ($R^2 = 0.96$ for 235 reflows) can be achieved for the relationship between the pressing number (N) and the T_r normalized to its initial value as follows:

$$T_r = a * N + b, \tag{2}$$

where a and b are the constants of linear fitting on the actual accumulated database. Evidently, the linear model is adequate for predicting the tactility of SMT-SREKs during the fatigue cyclic pressing test.

Based on a linear model (Equation 2), the forward T_r, as a lifetime index of SMT-SREKs, is projected with the accumulated T_r, which are received at the pressing number phase of 1.0E + 6 times. Similarly, a projection of forward T_r is implemented at the pressing phase of 1.5E + 6 times, 2.0E+6 times, and 2.5E+6 times. The error of predicted T_r to experimental T_r is less than 1% before the pressing number of 1.5E + 6 times and about 8% before 2.5E + 6 times (Fig. 15). Evidently, the prediction of SMT-SREK T_r is effective with the linear model before the pressing number of 2.5E+6 times.

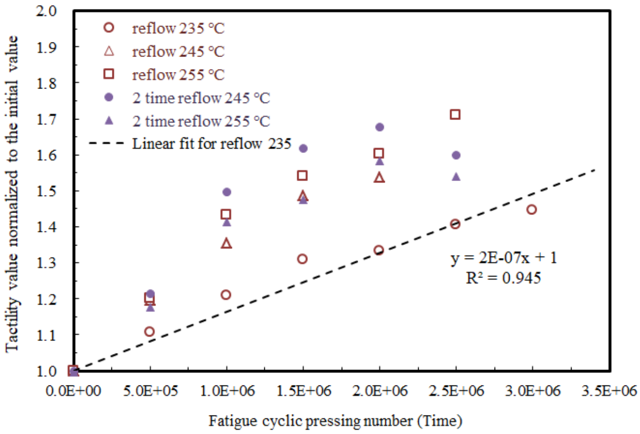

FIGURE 14. T_r with increasing fatigue cyclic pressing number.

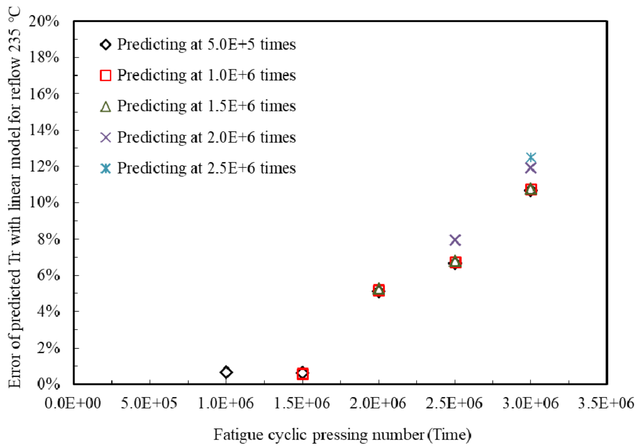

FIGURE 15. Error of predicted T_r with increasing pressing number for the reflowing condition at T_p of 235 °C.

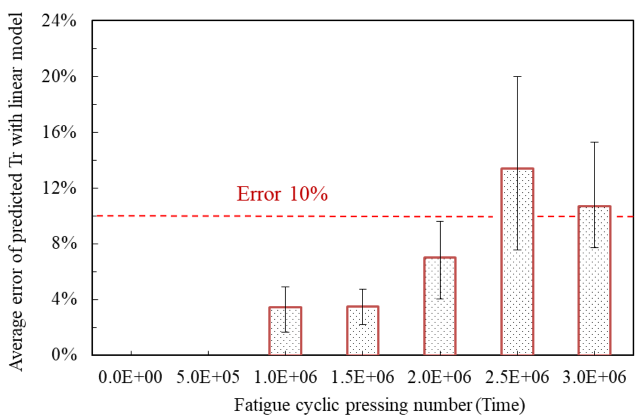

FIGURE 16. Average errors of predicted T_r with increasing pressing number for all reflowing conditions.

Moreover, average errors of the predicted T_r to the experimental T_r for three reflowing conditions are provided (Fig. 16). The average errors before the pressing number of 1.5E + 6 times are less than 4% and less than 7% before 2.0E + 6 times. However, the prediction errors increase by

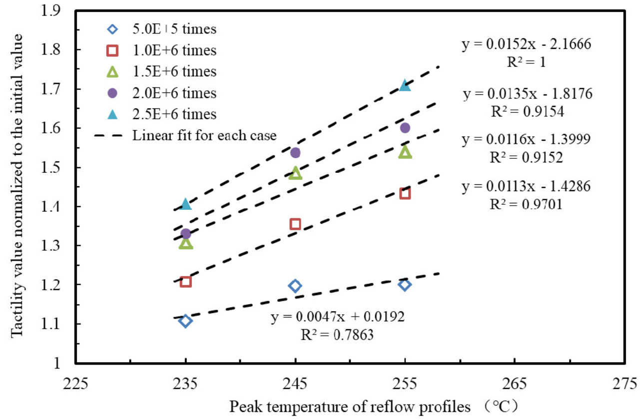

FIGURE 17. T_r with increasing T_p at different phases.

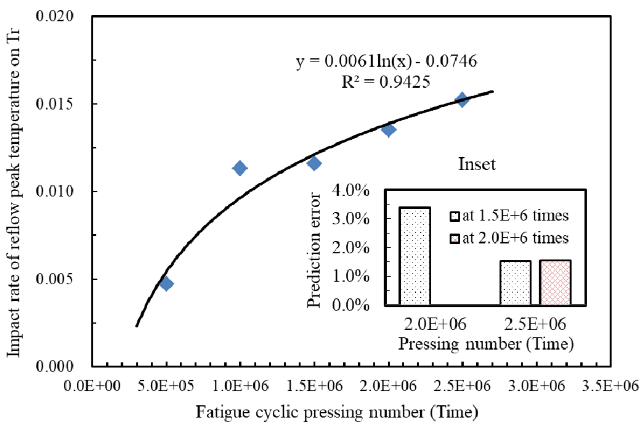

FIGURE 18. β with increasing fatigue pressing number (inset: error of forward predicted β).

more than 10% while the pressing number is over 2.5E + 6 times. This sudden increase is attributed to the exacerbating decay of silicone rubber materials in increasing reflowing temperatures, such as the degradation of hardness and compression set [13], and significantly affects the mechanical properties such as tensile strength and elongation [23]. Normally, the specification on the fatigue pressing number of general SREKs should be in a range of 1.0E + 5 to 1.0E + 6 times. Therefore, the linear model, which is suitable for projecting the pressing number within 2.0E + 6 times, can be applied for most products.

C. T_p EFFECT ON TACTILITY WITH INCREASING PRESSING NUMBER

T_r of each fatigue testing phase increases regularly in a manner of linear law with increasing T_p (Fig. 17). The impact rate of T_p on T_r, abbreviated as β, increases gradually in a logarithmic law and becomes stable when the pressing number is over 1.5E + 6 times (Fig. 18). The forward β is predicted using a logarithm model beginning with the pressing cycle of 1.5E+6 times (the inset of Fig. 18). The error of predicted β to the experimental one is less than 3.5%, which indicates that the logarithm model is a good candidate to express the relationship between β and the increasing fatigue pressing number. From the standpoint of optimizing long-term reliability, this finding is helpful to achieve an expected T_r in the phase of designing a thermal reflowing profile for manufactured SMT-SREKs.

IV. CONCLUSION

The mechanical pressing force and tactility of SREKs subjected to thermal reflowing degrade considerably although the duration of the reflowing process is extremely short because of the sudden thermal degradation of silicone rubber materials. Mechanical reliability is a major concern in the reflowing process. The circular transition between the conical hollow elastomer and the moving lug is the most dangerous position on SMT-SREKs. During the fatigue cyclic pressing test, T_r linearly changes with the increasing cyclic pressing number. The linear model is adequate for predicting the SMT-SREK tactility with an acceptable error before the fatigue pressing number of 2.0E+6 times. Meanwhile, the T_r change rate increases with T_p and can be accelerated by the repeated reflowing process before the pressing number of approximately 1.5E + 6 times. The logarithm model can determine the impact rate of T_p on T_r with the increasing pressing number. The findings of this study are significant for the qualification and normalization of novel SMT-SREKs in the future.

REFERENCES

[1] J. Tan, Y.-J. Chao, X. Li, and J. W. van Zee, "Degradation of silicone rubber under compression in a simulated PEM fuel cell environment," *J. Power Sources*, vol. 172, no. 2, pp. 782–789, 2007.

[2] D. Min, C. Yan, Y. Huang, S. Li, and Y. Ohki, "Dielectric and carrier transport properties of silicone rubber degraded by gamma irradiation," *Polymers*, vol. 9, no. 10, pp. 533–548, 2017.

[3] Y. Gao, Y. Yuan, L. Chen, J. Li, S. Huang, and B. Du, "Direct fluorination induced variation in interface discharge behavior between polypropylene and silicone rubber under AC voltage," *IEEE Access*, vol. 6, pp. 23907–23917, 2018.

[4] A. Saleem, L. Frormann, and A. Soever, "Fabrication of extrinsically conductive silicone rubbers with high elasticity and analysis of their mechanical and electrical characteristics," *Polymers*, vol. 2, no. 3, pp. 200–210, 2010.

[5] Y. Xue, X.-F. Li, D.-H. Zhang, H.-S. Wang, Y. Chen, and Y.-F. Chen, "Comparison of ATH and SiO_2 fillers filled silicone rubber composites for HTV insulators," *Compos. Sci. Technol.*, vol. 155, pp. 137–143, Feb. 2018.

[6] J. Guo, X. Chen, and Y. Zhang, "Improving the mechanical and electrical properties of ceramizable silicone rubber/halloysite composites and their ceramic residues by incorporation of different borates," *Polymers*, vol. 10, no. 4, pp. 350–388, 2018.

[7] X. Y. Chen *et al.*, "Design and analysis on SMT QFN silicone keypads," in *Proc. ICEPT*, Changsha, China, 2015, pp. 1022–1025.

[8] Z. Li, Z. Zhou, Y. Li, and S. Tang, "Effect of cyclic loading on surface instability of silicone rubber under compression," *Polymers*, vol. 9, no. 4, pp. 148–161, 2017.

[9] J. Qiu, X. Lai, H. Li, X. Zeng, and Z. Zhang, "Synthesis of zirconium-containing polyhedral oligometallasilsesquioxane as an efficient thermal stabilizer for silicone rubber," *Polymers*, vol. 10, no. 5, pp. 520–535, 2018.

[10] S. Chandrasekar, R. Sarathi, and M. G. Danikas, "Analysis of surface degradation of silicone rubber insulation due to tracking under different voltage profiles," *Elect. Eng.*, vol. 89, no. 6, pp. 489–501, 2017.

[11] H. Chang *et al.*, "Temperature and humidity effect on aging of silicone rubbers as sealing materials for proton exchange membrane fuel cell applications," *Appl. Therm. Eng.*, vol. 104, pp. 472–478, Jul. 2017.

[12] J. Zhang, S. Feng, and Q. Ma, "Kinetics of the thermal degradation and thermal stability of conductive silicone rubber filled with conductive carbon black," *J. Appl. Polym. Sci.*, vol. 89, no. 6, pp. 1548–1554, 2003.

[13] J. Wu, J. Dong, Y. Wang, and B. K. Gond, "Thermal oxidation ageing effects on silicone rubber sealing performance," *Polym. Degradation Stability*, vol. 135, pp. 43–53, Jan. 2017.

[14] X. Wang, S. Kumagai, and N. Yoshimura, "Relation between hydrophobicity and surface roughness of silicone rubber insulator before and after aging in acid rain," *IEEJ Trans. Fundam. Mater.*, vol. 119, no. 2, pp. 216–223, Feb. 1999.

[15] A. A. Al-Dharrab, S. B. Tayel, and M. H. Abodaya, "The effect of different storage conditions on the physical properties of pigmented medical grade I silicone maxillofacial material," *ISRN Dentistry*, vol. 2013, Mar. 2013, Art. no. 582051.

[16] P.-Y. Le Gac, V. Le Saux, M. Paris, and Y. Marco, "Ageing mechanism and mechanical degradation behaviour of polychloroprene rubber in a marine environment: Comparison of accelerated ageing and long term exposure," *Polym. Degradation Stability*, vol. 97, no. 3, pp. 288–296, 2012.

[17] N. O. Goga *et al.*, "Surface UV aging of elastomers investigated with microscopic resolution by single-sided NMR," *J. Magn. Reson.*, vol. 192, no. 1, pp. 1–7, 2008.

[18] A. Jha and A. K. Bhowmick, "Thermal degradation and ageing behaviour of novel thermoplastic elastomeric nylon-6/acrylate rubber reactive blends," *Polym. Degradation Stability*, vol. 62, no. 3, pp. 575–586, 2008.

[19] D. Oldfield and T. Symes, "Long term natural ageing of silicone elastomers," *Polym. Test.*, vol. 15, no. 2, pp. 115–128, 2008.

[20] Y. Zhu, K. Haji, M. Otsubo, and C. Honda, "Surface degradation of silicone rubber exposed to corona discharge," *IEEE Trans. Plasma Sci.*, vol. 34, no. 4, pp. 1094–1098, Aug. 2006.

[21] E.-S. Kim, H.-S. Kim, S.-H. Jung, and J.-S. Yoon, "Adhesion properties and thermal degradation of silicone rubber," *J. Appl. Polym. Sci.*, vol. 103, no. 5, pp. 2782–2787, 2007.

[22] B. Kim *et al.*, "A comparison among Neo-Hookean model, Mooney-Rivlin model, and Ogden model for Chloroprene rubber," *Int. J. Precis. Eng. Manuf.*, vol. 15, no. 5, pp. 759–764, 2012.

[23] S. Kashi *et al.*, "Mechanical, thermal, and morphological behavior of silicone rubber during accelerated aging," *Polym.-Plastics Technol. Eng.*, vol. 57, no. 16, pp. 1687–1696, 2018.

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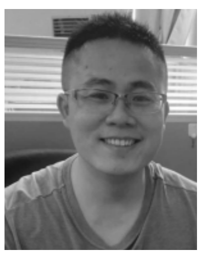

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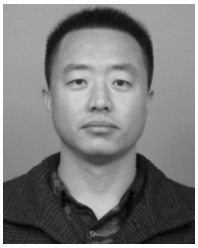

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