

Article

The Effects of Filler Shape, Type, and Size on the Properties of Encapsulation Molding Components

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Abstract: Fillers are essential in the encapsulation molding compound. For three fillers of crystal, spherical, and fused silica, the effects of their size, type, and shape on the viscosity, flow spiral length, thermal conductivity, and coefficient of thermal expansion (CTE) of the compound were explored in this study. The results show that fillers with a larger particle size have a smaller viscosity and flow better; spherical fillers are better than the polygonal ones in this respect. In contrast, both thermal conductivity and CTE increase as the filler particle size increases; the values of these two properties of crystal silica are about twice those of fused silica; the thermal conductivity of polygonal silica is larger than that of spherical silica. On the other hand, the dependence of CTE on the filler shape is insignificant, but is significant to the filler type. The degree of curing of the compound with polygonal silica is also higher than that with either spherical or crystal silica. Namely, curing is affected by both filler type and shape, and can be tuned accordingly to suit specific needs.

Keywords: encapsulants; thermal conductivity; curing; fillers; flow spiral length



Citation: Chao, S.; Liaw, Y.; Chou, J.-H. The Effects of Filler Shape, Type, and Size on the Properties of Encapsulation Molding Components. *Electronics* **2021**, *10*, 98. <https://doi.org/10.3390/electronics10020098>

Received: 3 December 2020

Accepted: 31 December 2020

Published: 6 January 2021

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1. Introduction

In consumer electronics, IC chips are always protected by resin-type encapsulation molding compounds (EMCs) in which silica (SiO₂) fillers are indispensable due to manufacturing and reliability needs. Because the amount of silica fillers in EMCs is generally high, they tend to affect EMC properties, such as the coefficient of thermal expansion (CTE), flow spiral length, glass transition temperature (T_g), thermal conductivity, etc.

These EMC properties closely relate to the device molding behavior and package reliability [1]. For example, the flow spiral length determines whether the EMC can be used for mass production or not. In the package molding process, the thermosetting EMC has to be melted first and then the package needs to be molded within a relatively short time period, which is determined by the EMC viscosity. Thus, a proper flow spiral length is crucial to avoid the occurrence of either incomplete filling (because of a small flow spiral length due to a larger viscosity) or overfilling (due to a large flow spiral length) of cavities, flash, etc.

Moreover, T_g affects CTE significantly, which in turn generates thermal stresses at the material interface. Thermal stresses could lead to delamination at the interface of the EMC and the leadframe [2–4] or substrate where the bonding is relatively weak. Therefore, reducing the CTE mismatch is essential to preventing delamination. In addition, T_g is also the key factor that affects the toughness of EMCs at elevated temperatures [5].

Theoretically, thermal stresses can be reduced by reducing the CTE mismatch or increasing the thermal conductivity to reduce the interface temperature. As the ratio of CTEs of silica filler to that of compound resin is about 1:100 [6], the CTE mismatch can be reduced by adding more silica fillers to the EMC [6,7]. Adding more silica fillers to EMCs can also enhance the flexural strength, increase the flow spiral length, reduce the moisture

absorption rate [8], and increase the thermal conductivity [9], which is very important in power electronics. However, adding more silica fillers reduces Tg [8] and lowers the adhesion force [9], which may not be desirable. Therefore, different aspects of silica fillers such as filler type [10] and size, which could affect the EMC properties, should be explored to seek alternatives, in addition to a larger amount of fillers, so that more choices can be selected for practical applications.

Thus, in this study, we examine experimentally the effects of filler shape (polygonal and spherical), type (fused and crystal), and size on the EMC properties relevant to manufacturing and package reliabilities, including the glass transition temperature (Tg), CTE, thermal conductivity, viscosity, and flow spiral length. The latter two properties are essential to curing, which can lead to residual stresses [11] or warpage [12], a critical issue for fan-out packages. In examining these properties, the filler amount is fixed to 75 wt% based on previous findings [8].

2. Experimental

The viscoelastic stress–strain relation of the resin-based thermosetting EMCs with respect to temperature variation [13] indicates that EMC curing depends on both temperature and time [14]. Hence, by measuring the torque versus time during curing, the strength of EMCs with various fillers can be determined.

Since fillers are powders, their sizes have certain variations, which can be described by their particle size distribution (PSD) and specific surface area (SSA). PSD is generally denoted by a nominal particle diameter such as D10, D50, or D90. Taking D10 = 4.475 μm as an example, the meaning of the nominal particle diameter is as follows: Let $V_{4.475}$ denote the total volume of all the particles with diameters being equal to or less than 4.475 μm and V represent the total volume of all the particles of the EMC. Then, D10 = 4.475 μm denotes all the particles of $V_{4.475}/V = 0.1$ (i.e., 10%). Hence, the medium particle diameter, D50, is commonly adopted as an indicator of the overall particle diameter.

SSA is the total surface area per unit mass (cm^2/kg) of all particles. Its value depends on the particle size: the smaller the size, the larger the SSA. Experimental details are as follows.

2.1. Silica Filler

The PSD of the fillers was measured by Malvern MS2000 (from Malvern Instruments, Malvern, UK) and is tabulated in Table 1 using code numbers. The capital letters F, C, and S preceding the numerals represent fused, crystal, and spherical fused silica, respectively.

Table 1. Filler type, shape, and particle size distribution (PSD).

Code	Type	Shape	PSD (μm)		
			D10	D50	D90
F01	Polygonal fused silica	P	3.1	15.8	59.5
F02	Polygonal fused silica	P	3.4	19.5	70.8
F03	Polygonal fused silica	P	4.6	30.3	95.0
F04	Polygonal fused silica	P	4.6	40.7	152.8
F05	Polygonal fused silica	P	4.7	45.3	163.5
F06	Polygonal fused silica	P	4.8	49.0	171.3
C01	Polygonal crystal silica	P	3.4	22.0	79.1
S01	Spherical fused silica	S	6.2	28.2	63.0

The symbols P and S of the shape column in the table represent the filler shapes of polygonal and spherical, respectively. For the polygonal fused silica, the particle size increased as the code number increased from 01 to 06; the medium particle diameter ranged from 15.8 μm to 49 μm . The corresponding values for polygonal crystal silica and spherical fused silica were 22.0 μm and 28.2 μm , respectively. Due to tight control of

the size distributions of the incoming silica particles, the standard deviation of PSD was about 6%.

2.2. EMC Composition

The composition of the EMCs is listed in Table 2, including the resin, hardener, filler, and others. The weight percentages of the resin, hardener, and others were fixed in this study, but not included due to proprietary concerns. The silica filler amount was also fixed to 75%; their type, shape, and PSD were varied, as illustrated in Table 1.

Table 2. Material composition of encapsulation molding compounds (EMCs).

Materials	wt%	Remark
Epoxy Resin	A	Epoxy equivalent MW: 200
Phenol hardener	B	Phenol equivalent MW: 105
Filler	75	Filler size as detailed in Table 1
Others	C	Wax, coupling agent, etc.

2.3. Measurement Instruments

T_g and CTE (α) were measured by a thermomechanical analyzer (TMA, Hitachi_TMA7100). The flow spiral length was measured at the mold temperature of 175 °C by injecting the EMC into the mold cavity with an injection pressure of 686 N/cm². The viscosity was measured by a Shimadzu CFT-100 viscometer. Curing characteristics were measured by JSR Curelastometer Model7 at 165 °C. The thermal conductivity was measured by a Kyoto Electronics QTM-500 thermal conductivity instrument.

2.4. Experimental Procedure

By referring to Tables 1 and 2, with the same EMC composition, the effect of particle size was examined by varying the PSD of fused silica fillers from F01 to F06. In addition, to compare the effect of silica types, the fillers with similar PSD but of different type (F03, fused silica; C01, crystal silica; S01, spherical fused silica) were explored.

3. Results and Discussion

3.1. Flow Spiral Length and Viscosity

The variation of the flow spiral length versus D₅₀ for polygonal fused silica fillers (F01 to F06) is depicted in Figure 1; the data standard deviation is denoted by σ . The result clearly indicates that, for polygonal fused silica fillers, the flow spiral length increased linearly as the filler size increased, indicating that EMC flows better by increasing the filler size. This trend was further evidenced by the results of EMC viscosity portrayed in Figure 2, which illustrates that for polygonal fused silica fillers, the EMC viscosity decreased as the filler size increased. The reason for this consistent trend in flow spiral length and viscosity is due to a smaller SSA as the filler size increased and thus resulting in smaller friction of flow. This trend is consistent with that of [15], which points out that the flow spiral length increased as the silica particle ratio D_L/D_S increased. The symbols D_L and D_S are the diameters of the silica fillers and silica sealing particles, respectively; a typical value of the latter was about 2 μm .

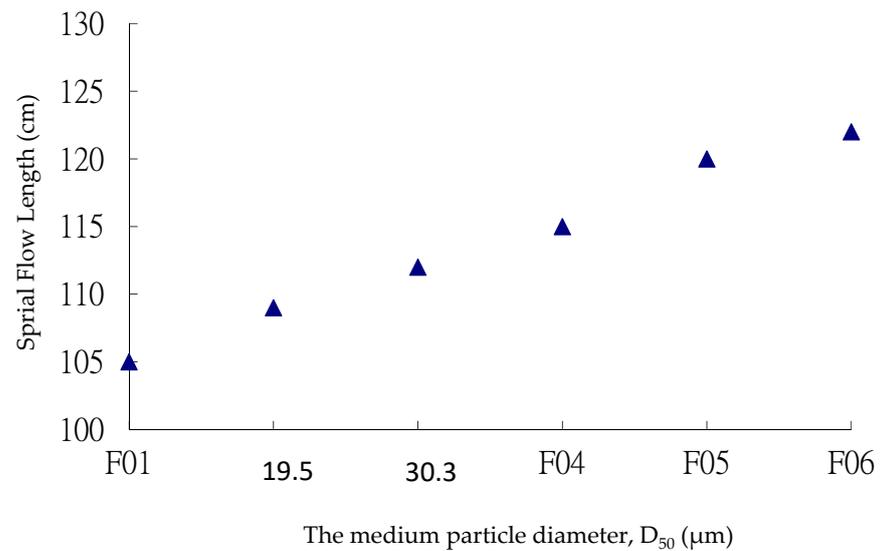


Figure 1. Flow spiral length versus D50 for EMCs with polygonal fused silica fillers (σ : 0.632 cm–1.356 cm).

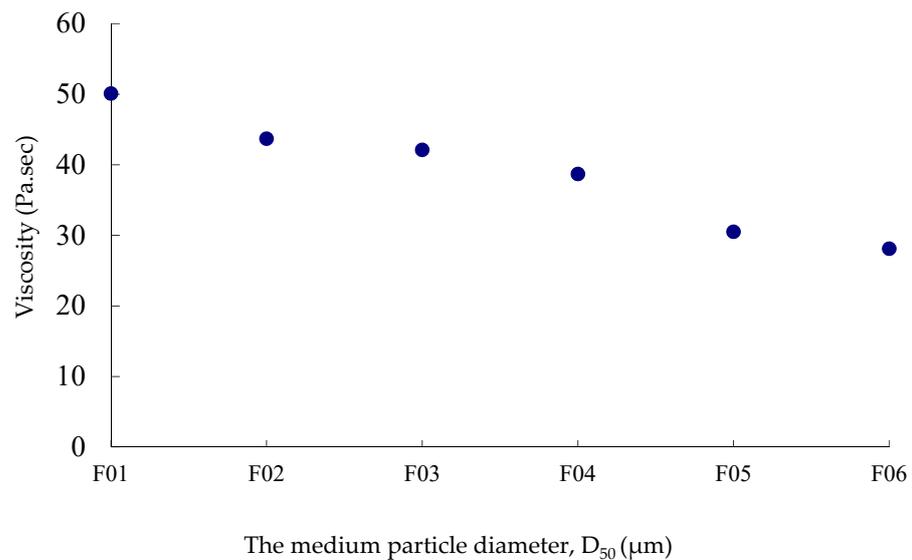


Figure 2. Viscosity versus D50 of EMCs with polygonal fused silica fillers (σ : 1.966–5.018 Pa·sec).

For the effect of silica types and shapes, the fillers of similar D50 were selected. For silica types, the D50 value of C01 was 22 μm , which was between those of F02 (19.5 μm) and F03 (30.3 μm). For silica shapes, the D50 value of S01 was 28.2 μm , which was close to that of F03 (30.3 μm). Hence, for simplicity, F03 was chosen for the comparison of both type and shape effects of fillers. The corresponding comparisons are shown in Figures 3 and 4, respectively. For the silica type effect exhibited by the polygonal fused silica (F03) and polygonal crystal silica fillers (C01), Figure 3a,b shows the comparisons of the spiral length and viscosity of the respective EMCs. The result indicates that the EMC with polygonal crystal silica fillers flowed slightly better. For the shape effect, the results portrayed in Figure 4 shows that the EMC with spherical fused silica fillers flowed better than that with polygonal fused silica fillers.

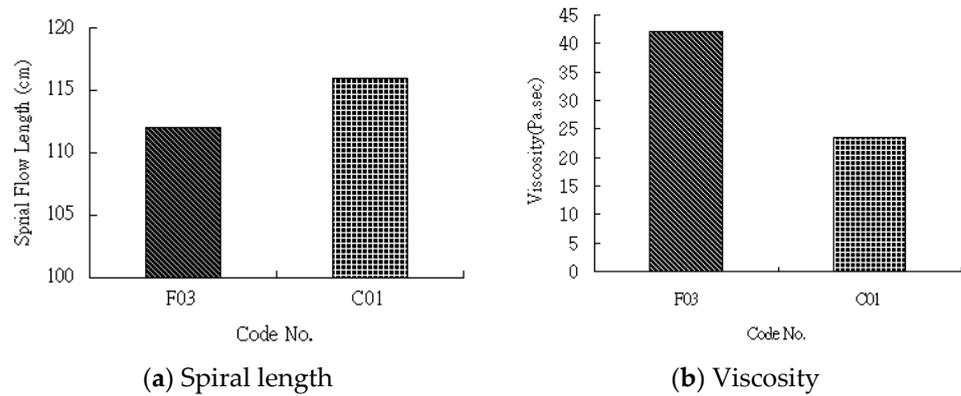


Figure 3. Filler type effects on spiral length and viscosity of EMCs.

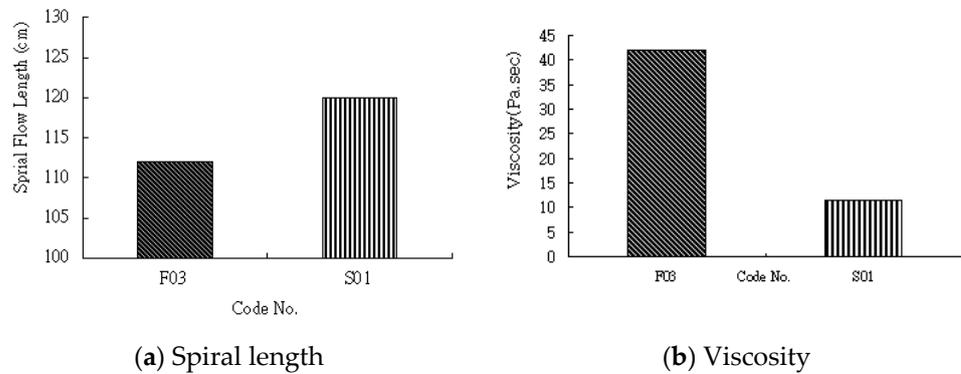
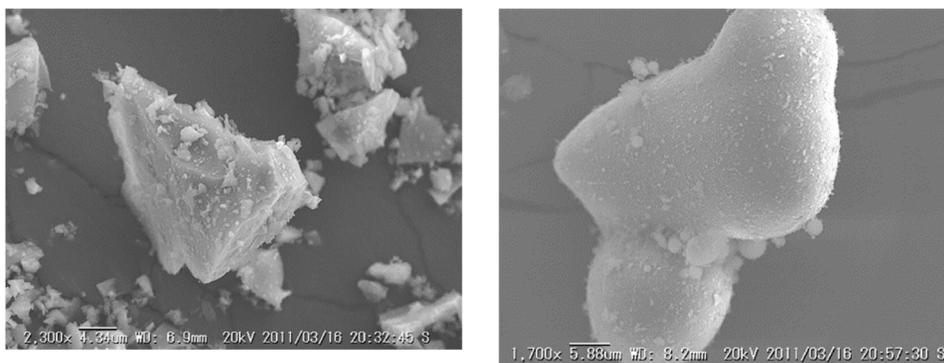


Figure 4. Filler shape effects on spiral length and viscosity of EMCs.

From the results shown in both Figures 3 and 4, it is clear that the shape had a larger effect than the type on the spiral length and viscosity of EMCs. As illustrated in Figure 5a,b, the main difference in shape between F03 and S01 was that the former was polygonal whereas the latter was spherical. The polygonal shape is multi-directional whereas the spherical shape is unidirectional; thus, the flow resistance of the latter was smaller than that of the former. This is also consistent with Mooney’s equation, which relates the Einstein constant (K_E) to the viscosity; a larger K_E leads to a larger viscosity. The K_E value of spherical particles was about 2.5 [16], whereas it was larger for polygonal particles due to a larger aspect ratio resulting from their slender shape.



(a) Polygonal fused silica (scale: 1/2300) (b) Spherical fused silica (scale: 1/2300)

Figure 5. Shape feature of polygonal and spherical silica (scale bars are 4.34 and 5.88 μm for (a) and (b), respectively).

On the other hand, the difference caused by polygonal F03 and C01 was due to specific gravity. The specific gravity of polygonal fused silica (F03) was 2.2 g/cm³, lighter than the 2.64 g/cm³ of the polygonal crystal silica (C01) [7]. Therefore, with conditions of the same weight and shape, the volume of F03 was larger than that of C01, as $\gamma_f V_f = \gamma_c V_c$, where the symbols γ and V stand for the specific gravity and volume, respectively, and the subscripts f and c denote F03 and C01, respectively. Thus, the EMC with C01 contained more epoxy and cured slower, thus leading to a longer flow spiral length and a smaller viscosity. Under similar conditions, the EMC with spherical fused silica fillers had the smallest viscosity and hence the largest flow spiral length due to its smaller flow resistance, as expected.

3.2. Thermal Conductivity

The thermal conductivity of the EMCs with fused polygonal silica fillers (F01 to F06) in terms of D50 is shown in Figure 6. The results reveal that the thermal conductivities increased linearly and slightly as the filler size increased. Overall, as shown in Figure 7, the EMCs with crystal silica fillers (C01) had the largest thermal conductivity, those with polygonal fused silica fillers (F03) the second, and those with spherical fused silica fillers (S01) the third.

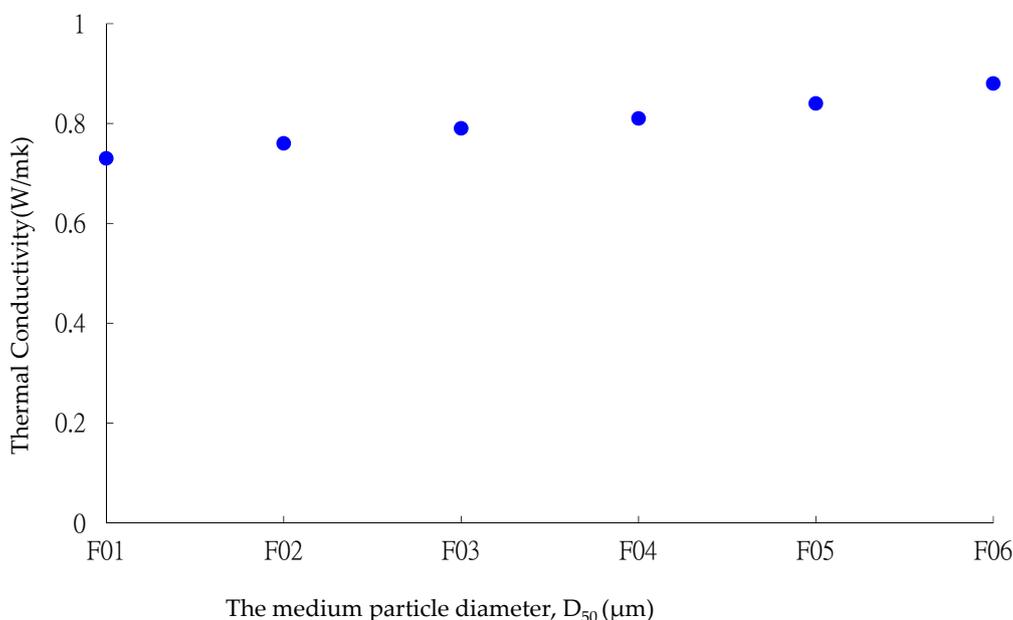


Figure 6. Thermal conductivities of EMCs with polygonal fused silica versus D50 (σ : 0.005 W/mK–0.008 W/mK).

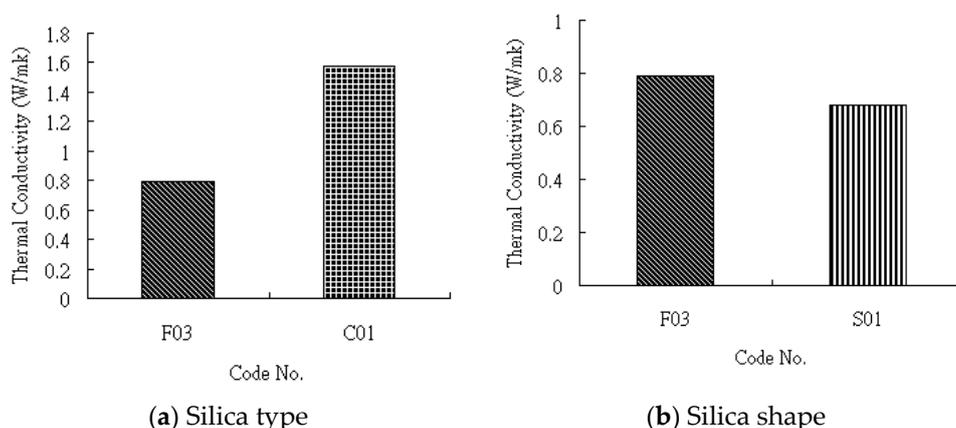


Figure 7. Thermal conductivity of EMCs with silica fillers of different types and shapes.

From Hasselman's model [17], the thermal conductivity of the EMC composite could be evaluated by the rule of effective thermal conductivities of the individual components (i.e., resin matrix and silica filler) using the idea of an equivalent diameter of the filler particles. A larger equivalent diameter implies a larger thermal conductivity. Moreover, as the thermal conductivity of crystal silica is about 10 times that of fused silica [9], and much larger than that of epoxy at 0.02–0.04 W/mk [15], the model indicates that the thermal conductivity of the EMC with C01 was larger than that with F03, as illustrated in Figure 7a.

In contrast, both F03 and S01 were fused silica of different shapes. The former was polygonal whereas the latter was spherical. The reason for the EMC with polygonal silica fillers having a larger thermal conductivity than that with the spherical silica fillers can be illustrated by the Lewis–Nielsen semi-empirical model [18]. The model shows that the thermal conductivity depends on the particle shape factor; a larger shape factor indicates a larger thermal conductivity. The shape factor is $K_E - 1$, where K_E is the Einstein constant ($K_E = 2.5$ for the spherical filler and was larger for the polygonal filler due to a larger aspect ratio, as stated previously). That is, the model indicates that the thermal conductivity of the EMC of F03 was larger than that of the EMC of S01, which is consistent with the results shown in Figure 7b.

3.3. CTE

The results of the CTE of the EMCs with various fillers are shown in Figures 8 and 9. It can be observed from Figure 8 that for the EMCs with polygonal silica fillers (F01 to F06), CTE increased slightly and nearly linearly as the filler size increased, consistent with the observations of [15], even though the increase was not significant. In contrast, the CTE of the EMC of C01 was about twice that of the EMC of F03, as in [10]. On the other hand, the CTEs of the EMCs of F03 and S01 were about the same because they consisted of the same type of fused silica fillers.

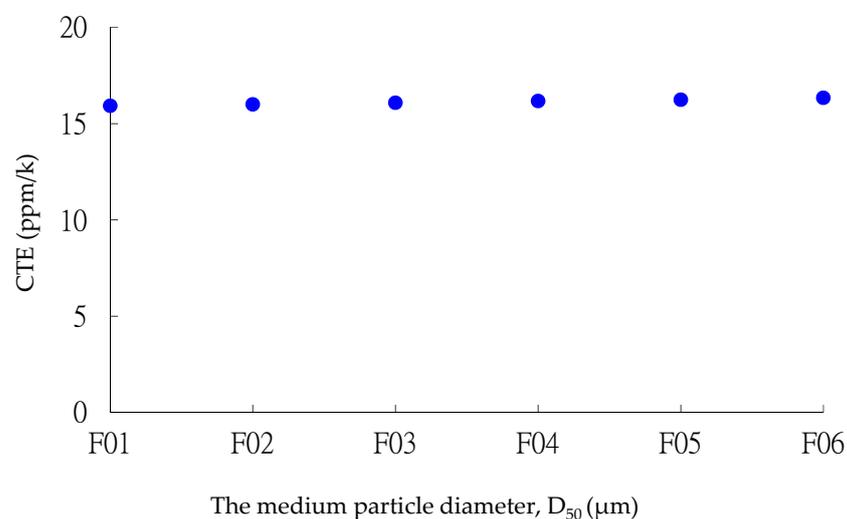


Figure 8. Coefficient of thermal expansion (CTE) versus D50 for polygonal fused silica (σ : 0.004 ppm/K–0.030 ppm/K).

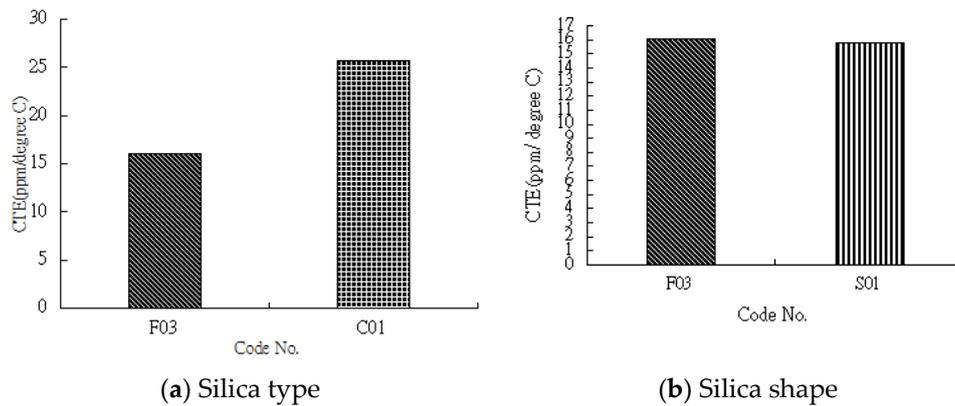


Figure 9. CTE of EMCs with silica fillers of different types and shapes.

The above observations indicate that the CTE depends strongly on the filler type, and slightly on the filler size, but not on the filler shape. As reducing CTE can reduce the package shrinkage [19,20], silica fillers can be used to adjust EMC qualities [21]. Hence, if the shrinkage of EMC is of great concern, then fused silica fillers with a smaller CTE [22] can be used. In addition, the viscosity of EMCs with fused silica fillers can be tuned to meet practical needs by shaping at the expense of a higher cost.

3.4. Curing Characteristics

The effect of filler sizes on curing in terms of EMC torque versus curing time is shown in Figure 10 for EMCs with fillers of F01–F06. The results show that with polygonal fused silica fillers, filler sizes had no significant effect on the curing characteristics of the EMCs. This feature can be explained by the Kamal–Sourour equation for the degree of curing α (from 0 to 100%), as $d\alpha/dt = k_0 \exp(-E/RT) \alpha^m (1 - \alpha)^n$ [23,24], which illustrates the relative independence of curing on particle sizes. Here, the symbols E, R, T, and t represent the activation energy, universal gas constant, absolute temperature, and time, respectively; m, n, and k_0 are constant.

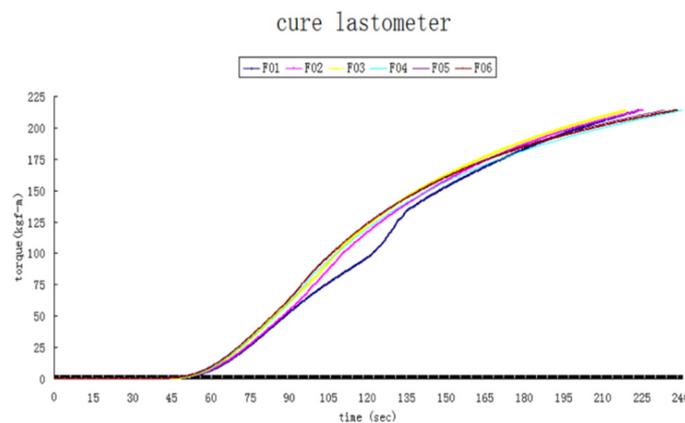


Figure 10. Effect of particle size on curing.

In contrast, the filler type did significantly affect EMC curing characteristics, as shown in Figure 11. That is, the degree of curing of the EMC with fused silica fillers (F03) was considerably higher than that with crystal silica fillers (C01) due to a larger spiral flow length of the latter. In general, a larger spiral flow length, because of the smaller viscosity, led to a longer curing time.

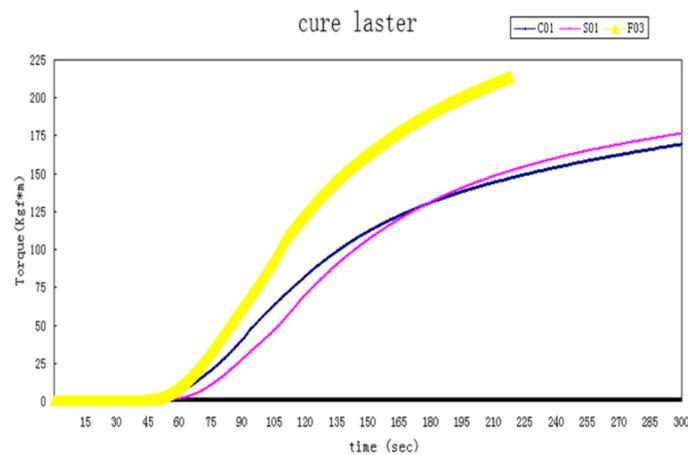


Figure 11. The effect of filler type and shape on curing.

Moreover, the filler shape also affected curing significantly by comparing the curing history of the EMCs with F03 (polygonal fused silica) and S01 (spherical fused silica). The shape effect on curing is related to the change in T_g , as shown by the DiBenedetto equation: $T_g(\alpha) = T_{g0} + ((T_{g1} - T_{g0})\lambda\alpha)/(1 - (1 - \lambda)\alpha)$ [25]. The symbols T_{g0} and T_{g1} represent the glass transition temperatures of $\alpha = 0$ and 100%, respectively; λ is the shape parameter, with values that ranged between 0.2 and 0.6. Furthermore, spherical fused silica fillers had a smaller K_E from the Mooney equation [16], thus leading to a smaller viscosity and larger spiral flow length, and resulting a longer curing time. In other words, the degree of curing α depended strongly on both filler shape and type.

It is interesting to note from Figure 11 that the curing characteristics of EMCs with either C01 or S01 were similar for the following reason. As stated previously in Section 3.1, crystal silica is heavier than fused silica. With the same weight percentage in the EMC, the volume of crystal silica is smaller, i.e., the resin amount is larger, hence, the EMC with crystal silica (C01) flowed better. On the other hand, spherical silica has less flow resistance due to its shape, hence, the EMC with spherical silica (S01) flowed better. These two contrasting trends of silica type and shape resulted in a similar flow behavior and led to similar curing characteristics of the EMC with fillers of either C01 or S01. Hence, these features can be utilized to tune the desired curing characteristic.

4. Conclusions

In this study, the effects of silica fillers on the properties of EMCs are examined experimentally. Key observations are as follows.

First, the viscosity, flow spiral length, and thermal conductivity of EMCs depend on the size, shape, and type of silica fillers. The EMCs with a larger filler size have a smaller viscosity and a larger flow spiral length. Spherical fillers have a lower viscosity and a larger flow spiral length due to their shape. The thermal conductivity of EMCs increases as the filler size increases. The thermal conductivity of EMCs with crystal silica is about twice that with fused silica, whereas polygonal fused silica leads to larger thermal conductivity than that of spherical fused silica.

Second, the CTE of EMCs is related to the filler size and type, but is not significantly dependent on shape. CTE increases as the filler size increases. Given that the CTE of EMCs with crystal silica is about twice that of fused silica, the filler type affects the CTE significantly.

Last, both filler type and shape affect the degree of curing significantly and can be used to tune the curing characteristics according to needs.

On the other hand, with further advances in the semiconductor fabrication towards the nanometer technology node of “More Moore,” trends of higher power dissipation and smaller bond pad pitch are expected. Moreover, the heterogeneous integration for

achieving more than Moore functions by fan-out technologies requires a larger package where warpage is of great concern. Therefore, EMCs with good thermal conductivity, larger spiral flow length, and matched CTE are essential. Hence, further studies for similar effects of crystal and spherical silica particles of various proportions to take advantage of their individual features would be beneficial for advanced packaging. Thus, continuous developments of both “More Moore and “More than Moore could be coped with even though the preparation of crystal and spherical silica particles is more time consuming.

Author Contributions: Conceptualization, S.C.; methodology, S.C.; software, S.C. and Y.L.; validation, Y.L.; formal analysis, S.C., Y.L., and J.-H.C.; investigation, S.C. and Y.L.; resources, J.-H.C.; data curation, S.C., Y.L., and J.-H.C.; writing—original draft preparation, Y.L.; writing—review and editing, S.C. and J.-H.C.; visualization, S.C., Y.L., and J.-H.C.; supervision, J.-H.C.; project administration, J.-H.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request due to proprietary concerns.

Conflicts of Interest: The authors declare no conflict of interest.

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