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Modelling of Thermal Aging of Moulding Compound by using an Equivalent Layer Assumption

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Abstract

Currently, the use of electronic components for automotive and aerospace applications is developing quickly. More and more components will be exposed to harsh environments, such as high temperature and high moisture. In general, this high temperature is always above the glass transition temperature (Tg) of the encapsulation material, being Epoxy Molding Compound (EMC). EMC exposed to high temperature could induce reliability problems of components due to changes of its material properties accompanied with volume shrinkage. Therefore, the characterization and modelling of the aging process in EMCs during high-temperature conditions has become an important issue. In our previous work [1], the characterization methods to obtain the material properties as function of aging time were discussed and introduced. The present work focuses on a new and efficient method to model the impact of the aging process of EMCs on the warpage and the stress state of a package using FEM simulation. Here, an "equivalent layer" model, which includes a fully oxidized layer and an unaged core, is applied to simplify the modelling of the thermal aging effects. The current thickness of the "equivalent oxidized layer" is obtained by combining the experimental results and numerical analyses of properly chosen samples. At the end of the paper the aging shrinkage is estimated by using the equivalent thickness concept

Introduction

As we know, the use of electronic components for automotive and aerospace applications is developing quickly. More and more components will be exposed to harsh environments, such as high temperature (above its glass transition temperature), high moisture content and so on. Among these, irreversible changes of the material properties of the encapsulation material (e.g. Epoxy Molding Compound - EMC) of the electronic components occur due to exposure to high temperature conditions. These changes can be attributed to chemical processes such as oxidation and degradation of the applied resins. After a certain time of exposure, a thin oxidation layer is created. This can be made visible by fluorescence microscopy. As a result, the thermomechanical properties, such as the viscoelasticity and the coefficient of thermal expansion, of the EMC change significantly with the progressing aging. Due to change in volume and in the material properties in the outside layer (aged layer) of the EMC, a mismatch between the aged surface layer and the unaged kernel occurs and this leads to changes in the state of stress and strain in a package. At the same time, embrittlement of the surface layer substantially influences its fracture strength. Consequently, the long-term reliability of a package is strongly affected.

According to the above problems, the characterization and modelling of the aging process in EMCs during high-temperature conditions has become an important issue. Many researchers showed that thermal aging has a significant effect on the thermomechanical properties of polymer based materials [2-6]. Various modelling methods for polymers were proposed and developed to model the aging process [7]. However, these modelling methods are not only complex, but also cannot simply be used within a standard FEM package.

In this paper a new and efficient model method, using an "equivalent layer concept", is introduced and shown. Based on this idea the impact of thermal aging on EMC will be modelled simplified by defining a so-called "equivalent thickness of the oxidation layer" with new (=changed) material properties. In our previous work [1], several measurement methods were developed to characterize the aged layer and the unaged core, separately. Meanwhile, the material properties being obtained from samples with different thicknesses and various periods of aging time are measured and shown in subsequent sections. Based on the experimental data and numerical simulations, the equivalent thickness of the oxidation layer was established as a function of the aging time. At the end the aging shrinkage is established while applying the equivalent thickness concept. For this simple model, further verification will be published later.

1. Two layers model - assumptions and verification

When EMC is exposed for long times at high temperature above its *Tg* the material properties will change significantly. This was found by many researchers. In Figure 1 two layers, the outer layer and the inner core, are visualized in the cross-section of a molding compound strip by fluorescence microscopy after several weeks of aging at high temperature in air. Based on this phenomenon the two layers model, where the outer layer is (fully) aged

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and the inner core is (fully) unaged, is proposed in the present work to simplify

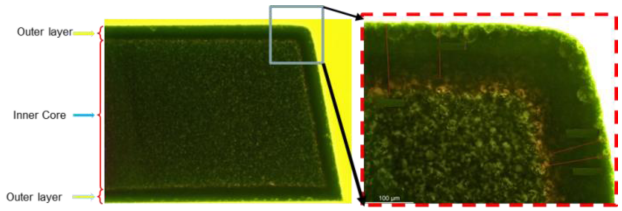


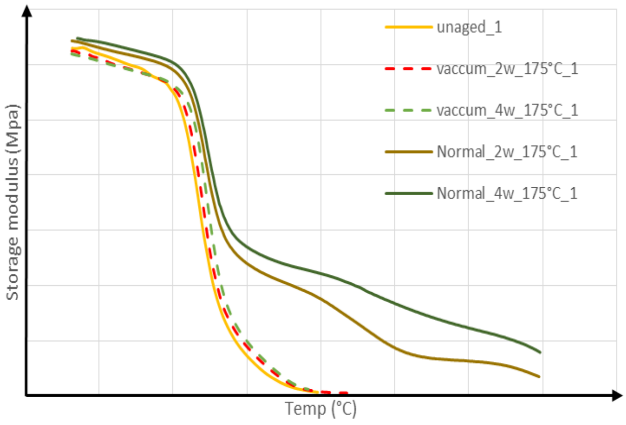
Fig. 1: Cross section of aged EMC

the modelling of the aging effects. To verify the two layers - model assumption, two tests were performed:
One test is storing samples of the same thickness in two different ovens: (Fig.2) one with air and one under vacuum at 175°C. The second test is storing samples of various thicknesses the oven with air at 175°C. After the same period of aging time the dynamic mechanical tests are performed by TA-Q800.

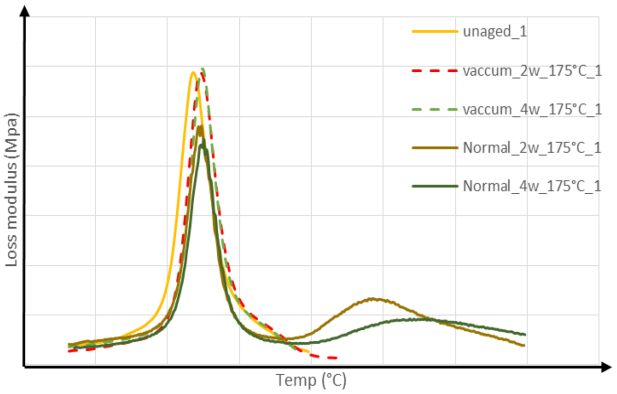
Fig. 2: Aging ovens: (right: vacuum, left: in air)

In Fig.3, the storage and loss moduli of fresh samples obtained from DMA tests at 1Hz were plotted, for samples aged in air (the solid lines) and under vacuum (the dashed lines) after 2 and 4 weeks aging at 175°C. The results of the storage and loss moduli show that the material properties after storage in vacuum are the same as for a fresh (unaged) sample. However, for high temperature storage under air the storage moduli are changing significantly with the aging time. In particular, the rubbery state is seriously affected. In addition, two glass transition temperatures are found after aging in air. Meanwhile, the first *Tg* value is almost the same as for the fresh sample, the second *Tg* value is much higher than the first *Tg* value and is increasing with the aging time. Two *Tg* values are observed in one sample. This indicates that a new substance is generated during thermal aging in the air oven, as we had already observed from Fig.1.

The second test is done by preparing samples of different thickness, one part of samples is thick and another is thin. In Fig.4, the storage modulus and Tandelta value vs. temperature are showed. Each picture includes two test results (green and red curves) to check the repeatability of the test method from sample to sample. The left side of Fig.4 shows test results of thick and thin unaged samples. Independent of the sample thickness the same material properties are found. The right side of Fig.4 shows test results after a certain aging time. The thick samples (upper right figure) has two T_g values and the thin samples (lower right figure) shows only one T_g value. The T_g value of thin samples is equal to the second T_g value of the thick samples. The first T_g value of the thick samples is the same as the fresh (unaged) samples. The conclusion is that the outer layers of the thick samples have the same T_g value as the thin samples. The core of the thick samples has the same T_g value as the fresh (unaged) samples.



a): Storage modulus of fresh and aged EMC



b): Loss modulus of fresh and aged EMC

Fig. 3: DMA test results of fresh and aged EMC

According to the above test results a two layers - assumption is suggested: after high temperature storage in air two parts exist in the EMC. The outer layer is the aged layer or oxidized layer and the inside layer is the unaged core. If the material properties of these two parts are established while the thickness of the oxidation layer as a function of aging time is known, then the "overall material properties" of a strip of molding compound could be predicted for any aging time.

However, the thickness of the oxidation layer can not directly be established from f.e. fluorescence microscopy. Reason for this is the fact that we can observe more than 2 layers (see Fig. 6). In reality, three layers exist in the molding compound after thermal aging (see Fig. 5): The outside layer is the fully aged layer (dark yellow) H_1, the

middle part is the reaction layer (yellow) H_2 and the core is the unaged (dark) part. Since the material properties of the

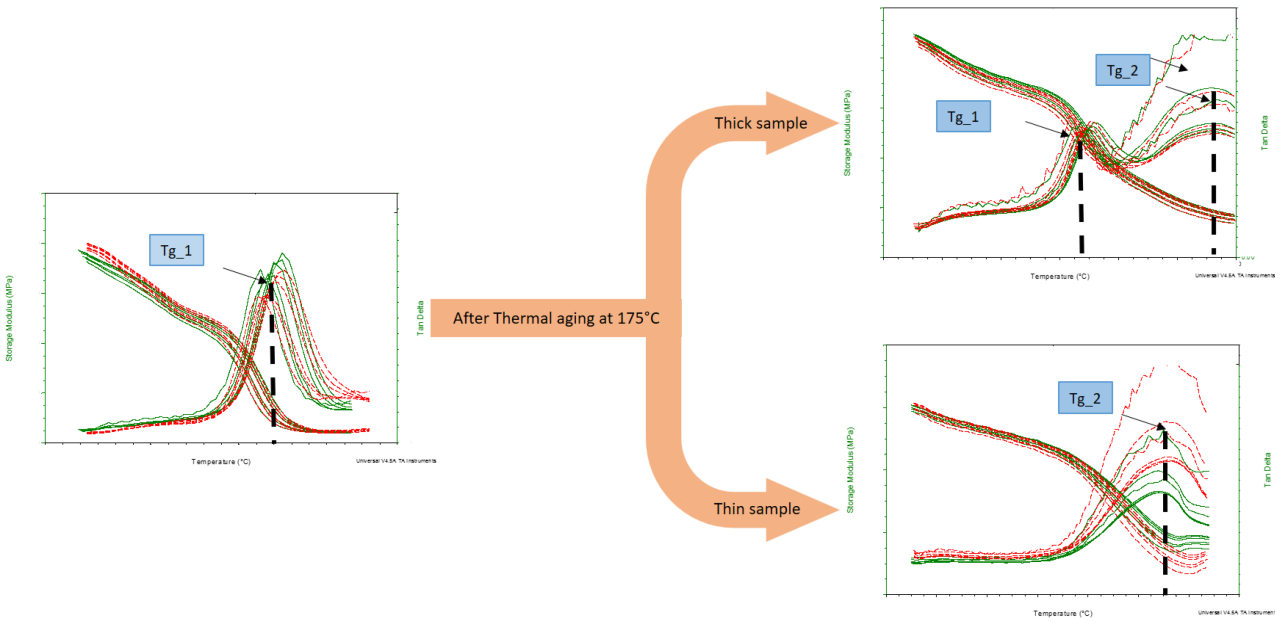


Fig. 4: DMA tests with thick and thin samples before and after aging

reaction layer since it cannot easily be established, a two-layer model with an "equivalent thickness" of the aged layer is proposed. Fig. 5 shows the schematic of this concept. It is assumed that the mechanical behavior can be modelled with sufficient accuracy, by modeling a fully aged equivalent layer and an unaged core material. The thickness of the equivalent layer should be established such that the "overall material properties" of a strip of molding compound could be well predicted for any aging time. Consequently, to establish the equivalent thickness of the oxidation layer (aged layer) with respect to the aging time is the main work in this paper.

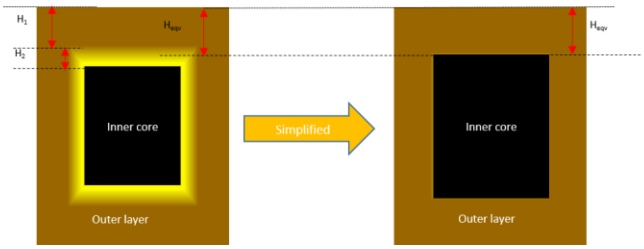


Fig. 5: schematic of equivalent thickness

thickness of the oxidation layer is aging time dependent as show in Figure 7. The measured points belong to 1 week up to 8 weeks aging at 175°C. The thickness of the dark yellow layer and the yellow layer of Fig. 5 are measured manually by a microscope. The upper curve is the thickness of $H_1 + H_2$ and the lower curve is the thickness of the dark yellow layer H_1. Fig.7 shows that the oxidation layer is growing quickly in the first week and after that the growth slows down with increasing aging time. Both curves include about 10 % deviation due to measurement observation errors.

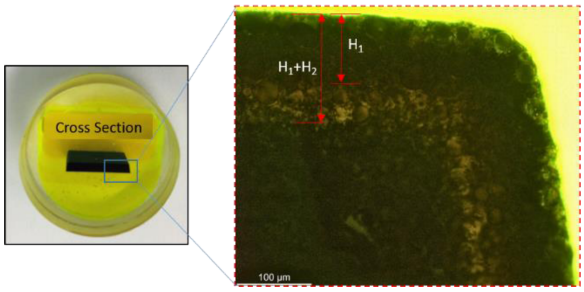


Fig. 6: Fluorescence microscope

2. Experimental Results and Discussion

In paper [1] the characterization methods are discussed in detail. In this section, only experimental results are shown and discussed.

2.1 Fluorescence microscopy

According to the procedure as described in the [2]. The oxidized layer in a partly aged sample is visualized by making a cross-section and becomes measurable by using fluorescence microscopy. Fig. 6 shows a cross-section of a thick sample after a certain aging time at 175°C. The

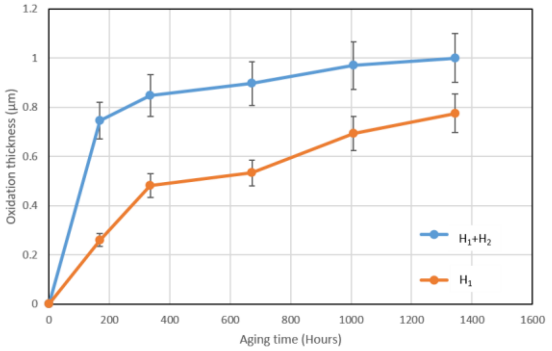
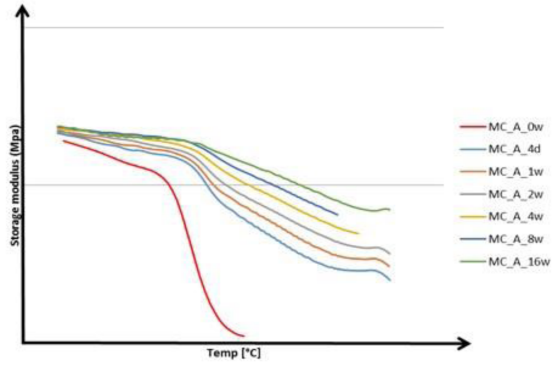
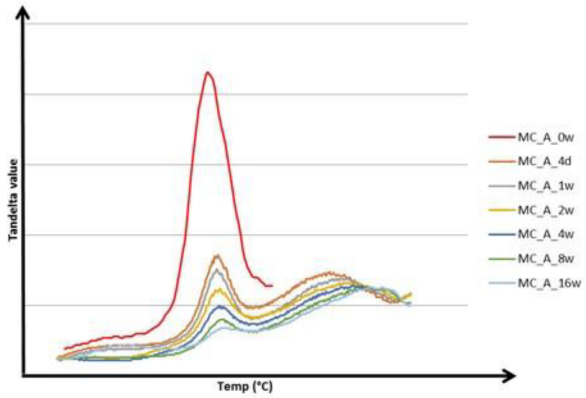


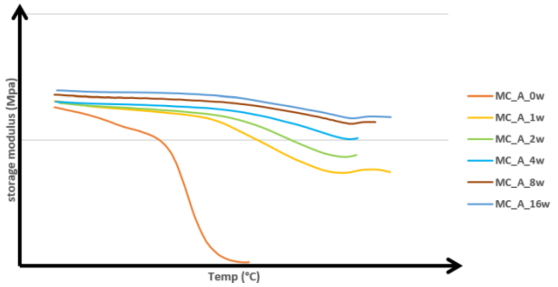
Fig. 7: (normalized) Oxidation thickness growth with respect to aging time



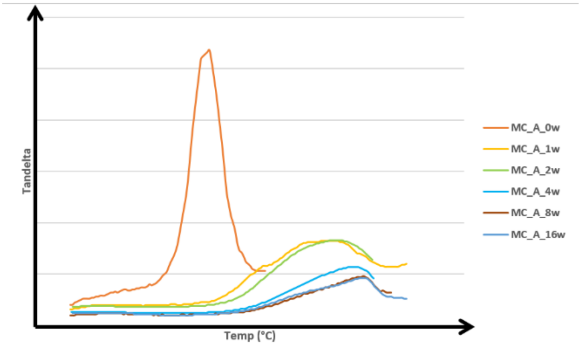
a) Storage modulus of unaged and aged thick samples



b) Tandelta value of unaged and aged thick samples



c) Storage modulus of unaged and aged thin samples



c) Tandelta value of unaged and aged thin samples

Fig. 8: Storage modulus and Tandelta value of thick and thin samples before and after aging

2.2 DMA test results

DMA tests were performed by a TA-Q800 device to explore the changes in the material properties of the EMC due to thermal aging effects. Thick and thin samples are measured at the same test conditions. Aged samples from 4 days to 16 weeks aging at 175°C were characterized. Here, the storage modulus and Tandelta value of (partly) aged samples and a fresh sample are plotted together with respect to temperature and 1Hz. Two peak values of Tandelta are observed in the thick samples and only one peak value was found in the thin sample as we also showed in Fig.4.

For thick samples the first peak value of Tandelta remains constant with increasing aging time. However, the second *Tg* value is increasing slowly after 4 days of aging. For thin samples only one peak value was found for various aged samples. It increases with aging time until 8 weeks of aging. The Peak value of 8 weeks is the same as the 16 weeks value. It means that the sample is fully aged after 8 weeks at 175°C. Consequently, the Tandelta value remains constant. The same phenomenon was found for the storage modulus after 8 weeks of aging. The material properties of the fully aged sample which are obtained here will be used later for simulations to establish the equivalent thickness of the oxidation layer.

2.3 Coefficient of thermal expansion (CTE)

As we know the initial stress in electronic packages is due to the mismatch of material properties. Among these, the CTE is the main factor. Therefore the determination of the CTE values after aging is also an important issue. CTE values of aged and unaged samples were measured by Thermal Mechanical Analysis (TMA). A temperature range from 0°C to 80°C is selected to establish the first CTE for $T< Tg$. A temperature range from 150°C to 250°C was selected to establish the second CTE which is for $T>Tg$. Figure 9 shows that the fresh sample has two CTE values. However, after 4 weeks of thermal aging only one CTE value was found (only for $T>Tg$). In figure 10, the normalized CTE values with respect to the aging time are presented. After long time aging at high temperature the

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CTE value is becoming constant. It also confirms that the material is fully aged.

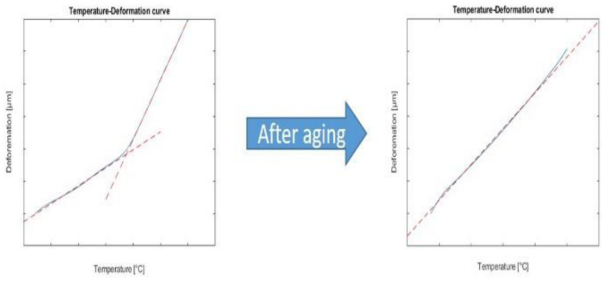

Fig. 9: Temperature-deformation curves. Left for a fresh sample; Right for an aged sample

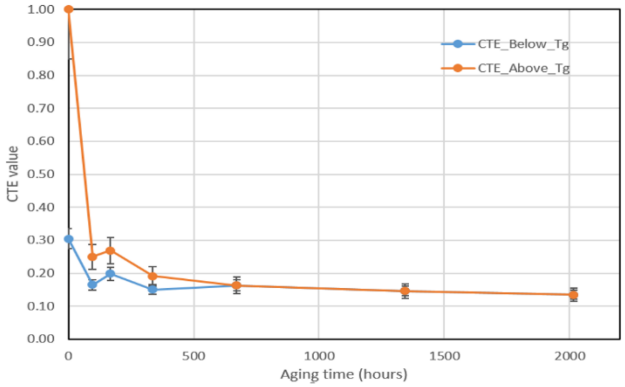

Fig. 10: (normalized) CTE value with respect to aging time

3. Establishment the Equivalent Thickness and the Aging Shrinkage

3.1 Equivalent Thickness of the oxidation layer

According to the above results, the equivalent thickness of the oxidation layer is established by combining the previous experimental results and numerical analyses.

In chapter 2 the fully aged sample is obtained after 8 weeks of aging at 175°C. The Finite Element Model used is presented in Figure 11. The unaged core is covered by an aged layer. The material parameters of fully aged material as measured before are used for the aged outer layer. The material parameters of the unaged material are applied for the core. Simulations are performed for various assumed outer layer thicknesses.

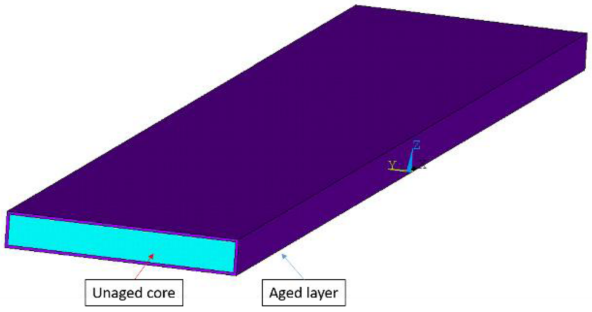

Fig. 11: FEM model

Comparison of the overall mechanical properties with the previous measurement results finally makes it possible to obtain the proper "equivalent thickness" for a given aging time. The so established (*normalized*) results of oxidation layer thickness (= "equivalent thickness") versus aging time are presented in Fig. 12, together with the experimental results from Fig. 7. The oxidation layer growth is following the empirical power law:

$$d = (\frac{t}{t_0})^{\alpha} + d_0 \qquad (1)$$

where, t is the aging time and t_0, α and d_0 are fitting parameters. As a result, the oxidation layer growth with respect to aging time could be computed by this function.

In Figure 13 the master curves of partly aged samples at 120°C from 4 days to 8 weeks aging at 175°C as predicted by the two layers model are presented. The solid lines are measurement results and the dashed lines are the simulation-prediction results.

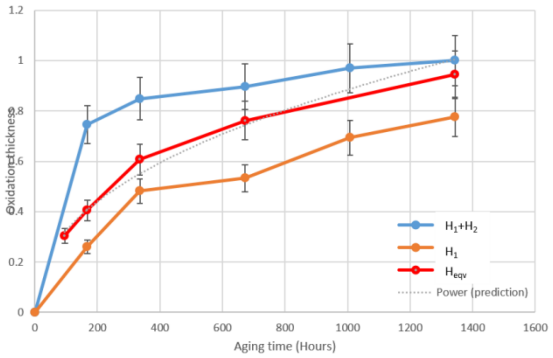

Fig. 12: Experimental results and Prediction results of oxidation layer growth (Equivalent Thickness)

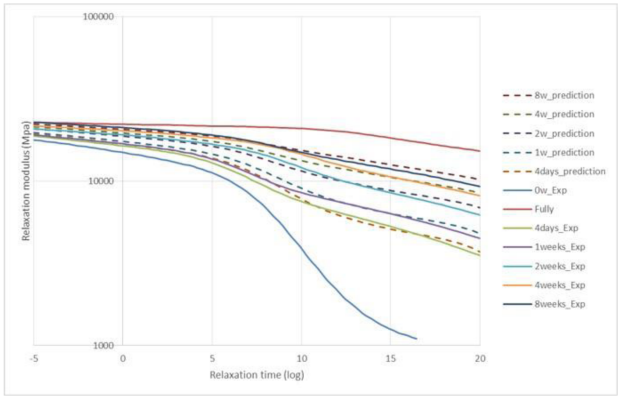

Fig. 13: Relaxation modulus of Partly aged sample predicted by fully and fresh sample

3.2 Aging shrinkage

From the DMA test results it was found that the thin sample used in this investigation needs 8 weeks to become "fully aged". That means that for establishing the aging shrinkage on samples of a certain thickness also long time tests would be required to end up with the aging shrinkage of a "fully aged" sample. Fig. 14 shows an aging-shrinkage test result obtained from a certain sample mounted in a TA-

Q800 DMA machine in the force controlled mode. Here, the axial force is remained approximately zero. The length change of the sample is monitored in real-time. The graph of Fig 14 shows the established strain versus the aging time together with a power low fit of the measurement data.

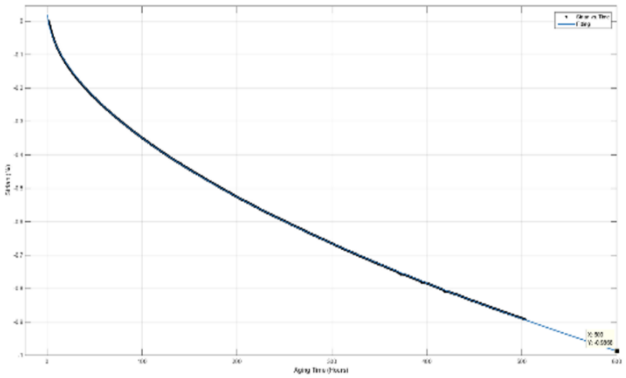

Figure 14: Aging shrinkage measurement by Q800

As can be observed from Fig.14, the "fully aged" state is not yet reached. Much longer aging tests would be required to end up in the "fully aged" state. However, since we have established the power law fit for the "Equivalent thickness" (1) and the power law fit of the aging shrinkage (Fig. 14), we do not need to proceed the shrinkage test to large aging times. On the basis of modelling based on the "Equivalent thickness" concept, the shrinkage of a fully aged sample can be established. It was found that the sample used will reach the "fully aged" at about 600 hours aging at 175°C.

4. Conclusions

A simple and efficient method to model thermal aging effects on material properties of EMCs was presented. First, the concept of a two layers - assumption is proposed and verified by experimental evidence. Secondly, the material properties, viscoelasticity and thermal expansion, of a molding compound with respect to aging time are fully characterized and shown. Finally, the equivalent thickness of the oxidation layer with respect to aging time is established by combining experimental and numerical results. The aging shrinkage of "fully aged" EMC is obtained based on the power law fit of the equivalent thickness and the power law fit of the aging shrinkage.

Reference:

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