01 Jan 2023

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Recommended Citation

L. M. Wilcox and K. M. Donnell, "Thermal Diffusivity Materials Characterization Via Active Microwave Thermography," *Conference Record - IEEE Instrumentation and Measurement Technology Conference*, Institute of Electrical and Electronics Engineers, Jan 2023.
The definitive version is available at https://doi.org/10.1109/I2MTC53148.2023.10175955

2023 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) | 978-1-6654-5383-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/I2MTC53148.2023.10175955

Thermal Diffusivity Materials Characterization via Active Microwave Thermography

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Abstract—Active microwave thermography (AMT) is a relatively new nondestructive evaluation method which is proposed in this work for thermal materials characterization. Specifically, AMT is investigated as a single-sided measurement option for out-of-plane thermal diffusivity (a parameter traditionally measured using a two-sided technique). Simulation and measurement results support the use of AMT for such a characterization for materials backed by an electromagnetically absorptive material. Both lossless and lossy materials may be measured, with better accuracy for lossless materials. The effect of heating time was also considered. The results indicate that for the 50 W system used here, 100 seconds of electromagnetic illumination is necessary to achieve less than 10% error in measured out-of-plane thermal diffusivity for lossless and lossy materials.

Keywords—Active Microwave Thermography (AMT), Materials Characterization, Nondestructive Testing and Evaluation (NDT&E), Out-of-Plane Thermal Diffusivity

I. INTRODUCTION

Within the realm of nondestructive testing and evaluation (NDT&E), there are numerous techniques that can be implemented depending upon the measurement needs (i.e., structure to be inspected, materials under consideration, defect type, etc.). One such well-established technique that is known for its ability to perform noncontact inspections over large areas is thermography [1]. Beyond traditional NDT&E, thermography can also be used for materials characterization, where properties such as thermal diffusivity [2], [3] of a material under test (MUT) can be measured. Historically, this measurement has been accomplished using a two-sided measurement approach. That is to say, heat is induced on one surface/side of a MUT, and the resulting surface thermal profile on the other side of the MUT is measured via a thermal camera [2]. As such, to perform such a measurement, both sides of the MUT must be accessible. This process is illustrated in Fig. 1. Since the requirement of access to both sides for characterization can be limiting, this work seeks to expand the capability of thermographic materials characterization by introducing another single-sided approach to measure out-of-plane thermal diffusivity. This approach is realized through the application of Active Microwave Thermography (AMT).

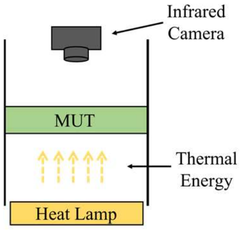


Fig. 1. Illustrative view of the a two-sided thermal measurement.

AMT is a subset of thermography that utilizes an electromagnetic-based thermal excitation. In AMT and assuming nonconductive materials, the thermal excitation is achieved through dielectric and/or magnetic absorption of the incident electromagnetic energy. This heating occurs volumetrically throughout the MUT. Thermal measurements are made on the surface of the MUT (as is done in traditional thermography) via an infrared camera. AMT has been successfully applied for NDT&E in several industries, most notably aerospace and infrastructure, with detection of defects including water ingress, delamination, and corrosion, amongst others [5]-[8]. When AMT is used for thermal materials characterization, the surface thermal profile is quantitatively analyzed to determine thermal properties of interest. Previously, AMT has been successfully utilized to measure the in-plane thermal diffusivity of a MUT [9]. This work seeks to expand the capabilities of AMT for thermal materials characterization by developing an approach for measurement of out-of-plane diffusivity using a single-sided measurement (i.e., electromagnetic excitation and measurement occur on the same/inspection side, with the thermal source induced electromagnetically on the back/opposite side of the MUT). In this way, through-transmission heating is maintained, a necessary requirement for out-of-plane thermal diffusivity measurement, but with thermal excitation and measurement occurring on the same side (i.e., a one-sided approach).

II. BACKGROUND AND SIMULATION

As mentioned, out-of-plane thermal diffusivity measurement is a well-established (two-sided) thermographic materials characterization technique [2]. For characterization, the out-of-plane thermal diffusivity, α, of a MUT is defined in terms of the thickness of the MUT, d, and the time required to reach half the maximum temperature, $t_{1/2}$ (where α is in mm^2/sec, d is in mm, and $t_{1/2}$ is in seconds), as [2]:

$$\alpha = 1.388 \cdot \frac{d^2}{\pi^2 \cdot t_{1/2}} \tag{1}$$

There is a typical thermal response that is measured when using the well-established two-sided measurement technique to measure α [2]. This response is qualitatively illustrated in Fig. 2, where the surface temperature resulting from through-transmission heating can be seen. Within this response, there are three major regions (as denoted in the figure): Region A – the early, flat period (i.e., the transit time of the heat through the sample from front to back), Region B – the increase in temperature due to heat diffusing through the MUT (i.e., nonzero slope), and Region C – the maximum temperature achieved (i.e., the slope approaches an asymptote). This response is important to understand and recognize as its presence in a measurement indicates that Eq. (1), above, is valid. It is also worth noting that the thermal excitation on the front face is assumed to be instantaneous for traditional measurement of α (i.e., a single pulse of thermal energy is radiated from a heat lamp). Additionally, these responses shown in Fig. 2 represent the ideal scenario, and measurements will resemble but not match these curves/regions.

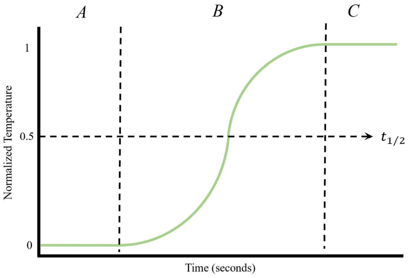


Fig. 2. General surface thermal profile for through transmission heating.

As mentioned previously, AMT is based on dielectric and magnetic absorption of incident electromagnetic energy. The ability to store and absorb this energy is quantified by the dielectric and magnetic properties, ε and μ, respectively. Both are complex and, when referenced to free space properties (ε_0 and μ_0, respectively), are denoted as $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$ and $\mu_r = \mu_r' - j\mu_r''$, respectively. Here, ε_r' and μ_r' (the real parts) are the permittivity and permeability, respectively, and represent the ability of a material to store electromagnetic energy. The imaginary parts, ε_r'' and μ_r'' (electric, and magnetic loss factors, respectively), quantify a material's ability to absorb electromagnetic energy. This absorbed energy is relevant to AMT as it is converted into heat, Q, as [10]:

$$Q = 2\pi f (\varepsilon_0 \varepsilon'' |E|^2 + \mu_0 \mu'' |H|^2) \tag{2}$$

where f is the frequency, E is the incident electric field, and H is the incident magnetic field. As a note, it is not currently possible discriminate between the heat generated from electric field absorption and the heat generated from magnetic field absorption during an AMT measurement.

To validate the potential for out-of-plane thermal diffusivity measurement utilizing AMT, a coupled electromagnetic-thermal simulation was completed using CST Microwave Studio™. This simulation considered a MUT consisting of a lossless material (neoprene rubber) placed on top of a material with a high loss factor (radar absorbing material, or RAM). This MUT was designed to represent structural scenarios that contain a material of interest backed by a known absorbing material (e.g., RAM, glue, etc.) The cross section of the rubber and RAM is 10 cm × 10 cm. The thickness of the rubber and RAM is 4 cm and 0.4 cm, respectively. An illustrative view of this MUT can been seen in Fig. 3.

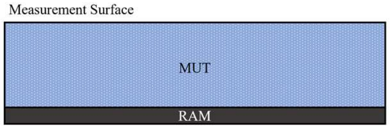
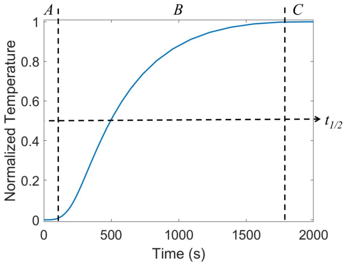


Fig. 3. Illustrative view of the MUT used in simulation.

These two materials were selected for the simulated MUT because the lossless material allows for the electromagnetic energy to travel, with no signal attenuation/absorption, through the structure to the RAM. The RAM, due to its high loss factor, absorbs most of the incident electromagnetic energy and hence heat is generated. As such, AMT is used to generate a thermal source on that back side of the MUT (here, within the RAM). Then, the heat from this induced source diffuses back to the inspection side, where the surface thermal profile is measured. In this way, a through-transmission thermal measurement is made, but with access to a single side of the MUT. As mentioned, such a measurement may be made practically any time there is an electromagnetically absorptive material (RAM, glue, etc.) behind a material of interest. As such, the RAM-backed case is considered here as an illustrative scenario.

During this simulation, 50 W of microwave energy was radiated from a standard gain ridged horn antenna (aperture dimensions of 23 cm × 17 cm) placed 40 cm above the surface of the MUT. A frequency of 2.4 GHz was used since the RAM used later for measurements exhibits high absorption of microwave energy at this frequency. It is worth noting that while RAM was used in this simulation (and the following measurements), a lossy glue, polymer, or epoxy that is part of an existing structure of interest may accomplish the same task (i.e., an electromagnetically absorptive heat source) as the RAM in this work. The MUT was exposed to 150 seconds of electromagnetic energy (i.e., the heating time), with thermal observations continuing after cessation of microwave illumination (i.e., the cooling time). The thermal boundaries of the MUT are considered adiabatic (i.e., heat transfer is absent through the boundary). Fig. 4 displays the simulated normalized (to the maximum) temperature at the center of the measurement surface. As seen, the results here include the same trends of Fig. 2, with all three regions described previously evident and noted in Fig. 4. This supports the application of AMT as a viable single-sided measurement approach for through-transmission heating and subsequent measurement of out-of-plane thermal diffusivity. As such, measurements of the same were conducted with the results reported in the next section.



Heating Time = 150 seconds

Fig. 4. Simulated normalized surface temperature of the MUT.

III. MEASUREMENTS

To show the efficacy of AMT for out-of-plane thermal diffusivity characterization, measurements were conducted on a MUT similar to that of simulation. More specifically, Fig. 5 shows the MUT (herein referred to as MUT-1), consisting of a piece of rubber and Cuming Microwave C-RAM FF-2 magnetic type absorber, selected due to its high magnetic loss at 2.4 GHz [11]. The rubber had a cross-section of 30.5 cm × 30.5 cm with a thickness of 12.7 mm. The RAM had a cross-section of 30.5 cm × 30.5 cm with a thickness of 2.4 mm. The electromagnetic energy was incident on the rubber face (inspection surface).

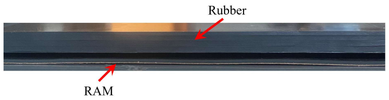


Fig. 5. Side view of MUT-1.

A photograph of the AMT system used for measurements is shown in Fig. 6. The system employs a ridged horn antenna, with aperture dimensions of 23 cm × 17 cm, to transmit the electromagnetic energy and operates over a frequency range of 1-3 GHz. The frequency is controlled by a microwave source and is amplified to 50 W of radiated power. The infrared camera used to capture the surface thermal profile is a FLIR T430sc infrared camera with a thermal sensitivity of 30 m°K. A data acquisition unit (DAQ) and computer are used to synchronize all components of the system. A heating time of 150 seconds was used, followed by a cooling time of 450 seconds (i.e., the microwave excitation is no longer active but thermal measurements continue). The temperature across the measurement surface, over the measurement period, is measured with an infrared camera and the thermal diffusivity calculated using Eq. (1).

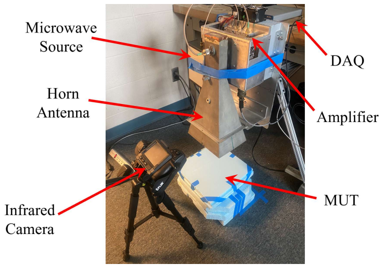


Fig. 6. AMT measurement setup.

Fig. 7 displays the normalized average surface temperature of MUT-1, calculated over a 5 × 5-pixel area in the center of the MUT (0.75 cm × 0.75 cm surface area). The measurement was normalized to the maximum temperature measured during the measurement period and reported relative to ambient. Additionally, to further reduce the impact of noise on the determination of $t_{1/2}$, a 3rd order polynomial curve fit was used. The results shown here include all three regions (*A*, *B*, and *C*) of Fig. 2, supporting this approach for measurement of out-of-plane thermal diffusivity. The regions are shown (in Fig. 7) by the dashed, black, vertical lines with the respective region labels for figure clarity and ease of comparison with Fig. 2. These lines were placed through visual approximation per the definition of the regions provided above. Moreover, this response (indicative of limited volumetric heating as per Region *A*) was expected as the rubber is very low loss (ε_r = 5.41 - j0.05 as measured using the open-ended waveguide technique with a modified flange [12]). As such, a majority of the heat present on the measurement surface is due to the energy absorbed by the RAM that has diffused back to the measurement surface. From Fig. 7, $t_{1/2}$ occurs at 266 seconds. Using Eq. (1) with this $t_{1/2}$, the thermal diffusivity of the rubber was calculated as 0.1276 mm^2/s. For comparison, this material was also measured by Thermal Wave Imaging, Inc using the approach of [2], with a result of 0.1355 mm^2/s. The good agreement between the proposed AMT approach and that of [2] is encouraging as it relates to the viability of the new technique.

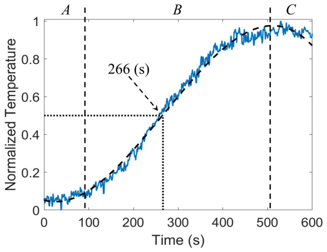


Fig. 7. Normalized AMT measurement results from MUT-1.

While the results above are very encouraging for the new measurement approach, many practical materials are not effectively lossless. To this end, another MUT, MUT-2, was designed that included rubber with a higher loss factor (measured $\varepsilon_r =$ 5.02 - j0.43 as per [12]). In this way, volumetric heating of the rubber will take place when under AMT illumination. Measurements were performed on this MUT, with Fig. 8 displaying the normalized (to the maximum measured value) average temperature, relative to ambient, over a 5 × 5-pixel area in the center of the MUT (0.75 cm × 0.75 cm surface area). Again, a 3rd order polynomial curve fit was used to reduce the impact of noise on the determination of $t_{1/2}$.

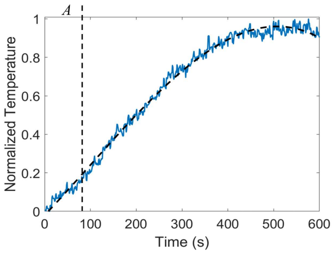


Fig. 8. Normalized AMT measurement results from MUT-2.

The results shown here indicate a different behavior for Region A than those of Fig. 7. That is to say, the early flat slope defined in Fig. 2 is absent. This indicates that instantaneous heating of the MUT took place during the measurement, as was expected due to the increased loss factor of the rubber. This is a concern as it relates to the measurement of out-of-plane diffusivity since it is the diffusion of heat through a MUT that is the basis for the measurement. As such, measurements were performed on the neoprene rubber of MUT-2 alone (i.e., MUT-2 without the RAM present), with the results shown in Fig. 9, normalized to the maximum temperature of Fig. 8.

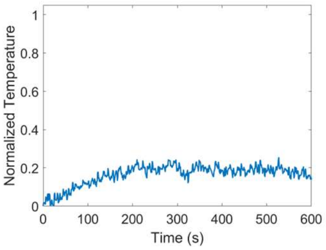


Fig. 9. Normalized AMT measurement results from the neoprene rubber of MUT-2.

This measurement was done in order to characterize the direct heating of the rubber. In this way, the effect of direct heating may be removed from the results of Fig. 8. It is clear from Fig. 9 that the material directly absorbs some of the incident energy, with a temperature increase of ~20% relative to that of MUT-2. Therefore, to remove the effect of this direct heating of the rubber, the results of Fig. 9 were temporally subtracted from those of Fig. 8, with the outcome shown in Fig. 10 and referred to as "corrected" (along with the result for MUT-2, or "uncorrected", for comparison). It is important to note that the corrected results were normalized to the respective maximum. This is necessary in order to deduce $t_{1/2}$ for the corrected results to calculate thermal diffusivity.

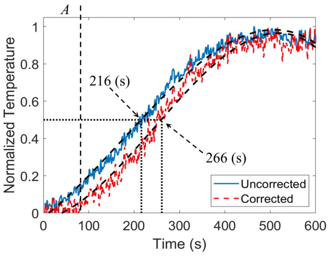


Fig. 10. Normalized results of MUT-2 with and without correction.

Here, the expected curve shape that is consistent with through transmission heating is evident in the corrected results (the early flat slope of Region A). From Fig. 10, $t_{1/2}$ occurs at 266 seconds for the corrected response of MUT-2, whereas $t_{1/2}$ occurs at 216 seconds without the correction. Using Eq. (1), the thermal diffusivity was calculated as 0.1276 mm^2/s for the corrected results, and 0.1486 mm^2/s for the uncorrected. The measurement from Thermal Wave Imaging, Inc. for the same sample is 0.1613 mm^2/s, and the established thermal diffusivity is 0.164 mm^2/s for this material [13], [14]. A summary of these results (and those of MUT-1) is provided in Table 1.

Table 1: Summary of Thermal Diffusivity Results

Material		***Thermal Diffusivity (mm^2/s)***	
		AMT	Established
MUT-1		0.1276	0.1355
MUT-2	Uncorrected	0.1486	0.1613
	Corrected	0.1276	

As can be seen in Table 1, the out-of-plane thermal diffusivity calculated from the uncorrected AMT measurement (i.e., Fig. 8) is a closer approximation to the established value. In other words, the attempted correction for the AMT measurement has not improved the calculated result and hence this step is not recommended. Additionally, the established approach and equations were derived for the use of a flash heat lamp source (i.e., radiative, and convective heating) [2], while this proposed approach utilizes conductive heating. As such, the difference in heat transfer is a contributor to potential error. Good agreement is also noted between the value from Thermal Wave Imaging, Inc. and the established value, indicating that the effect of volumetric heating in this case was minimal. Overall, these results indicate that the AMT approach can provide a general idea of the out-of-plane thermal diffusivity. However, if a precise measurement is needed, another approach must be taken. In addition, this approach presents a potential solution for scenarios in which the established method cannot be applied.

To further illustrate the capabilities of the proposed approach, an additional MUT was considered. Since the previous results are promising for measurement of lossless materials, foam was selected (referred to as MUT-3). The foam had a cross-section of 30.5 cm × 30.5 cm, and a thickness of 5 cm. Fig. 11 displays the normalized (to the maximum measured value) average temperature, relative to ambient, over a 5 × 5-pixel area in the center of MUT-3 (0.75 cm × 0.75 cm surface area), in addition to the fitted polynomial. Similar to MUT-1, the measurement displays the expected curve shape (i.e., Fig. 2), with the relevant regions shown with labels (in Fig. 11) by the dashed, black, vertical lines. From Fig. 11, the $t_{1/2}$ occurs at 185 seconds which results in a calculated thermal diffusivity of 1.9005 mm2/s. While thermal diffusivity of this material is inherently difficult to calculate by the established approach, it can be calculated through thermal conductivity, specific heat, and density and is calculated as 1.9320 mm2/s per [15]. The good agreement between the AMT-based approach and estimated value calculated from other material properties [15] reinforces the use of this approach for lossless materials.

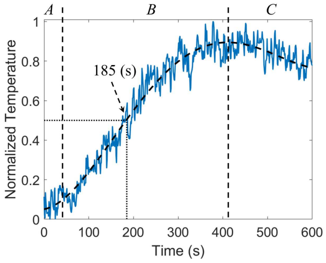


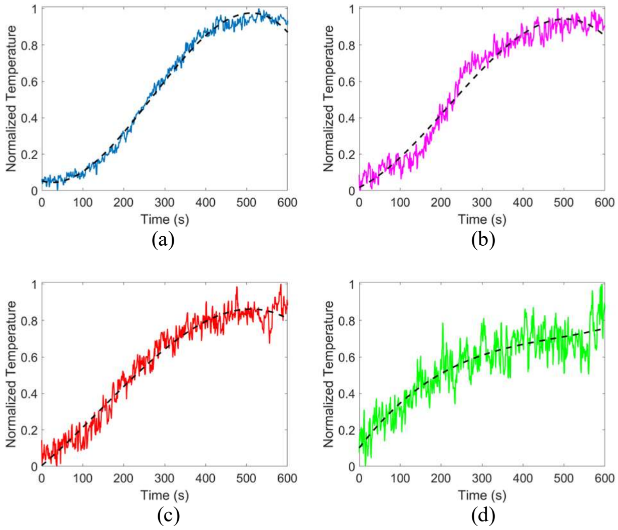
Fig. 11. Normalized AMT measurement for MUT-3.

A. *Effect of Heating Time*

As has been shown, AMT offers a viable alternative for accurate measurement of out-of-plane thermal diffusivity for low loss materials, and an estimate of the same for lossy materials. As such, the effect of heating time must also be known in order to ensure that an appropriate heating time has been used for measurement. To this end, heating times of 150 (as above), 100, 50, and 25 seconds are experimentally considered for both MUT-1 and MUT-2. No correction was used for the results of MUT-2, as this was shown above due to the degradation of the measurement. The thermal response and thermal diffusivities (including error) are shown in Fig. 12 and Table 2 for MUT-1, and in Fig. 13 and Table 3 for MUT-2. The error reported is calculated as:

$$\%\,ERROR = \left|\frac{Experimental - Actual}{Actual}\right| \times 100 \tag{3}$$

where *Experimental* is the calculated value and *Actual* is the known thermal diffusivity (per [13] and [14]) of 0.136 mm^2/s for MUT-1 and 0.164 mm^2/s for MUT-2.



(a) (b)

(c) (d)

Fig. 12. Normalized AMT thermal diffusivity measurements of MUT-1 for heating times of: 150 seconds (a), 100 seconds (b), 50 seconds (c), and 25 seconds (d).

Table 2: Thermal diffusivity and error for MUT-1

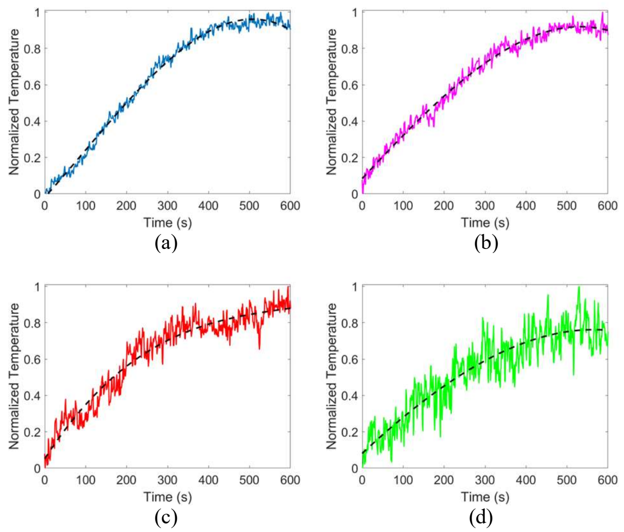
Heating Time (s)	***$t_{1/2}$ (s)***	***Thermal Diffusivity (mm^2/s)***	***Error (%)***
150	266	0.1276	6.18
100	234	0.1352	0.59
50	231	0.1370	0.74
25	195	0.1623	19.34

For the lossless material, MUT-1 (i.e., Fig. 12 and Table 2), as the heating time decreases (Fig. 12a to Fig. 12d), it is clear that the noise, relative to surface temperature, increases. This causes an increase in the error of the calculated thermal diffusivity (i.e., 25 seconds). While the increase in error was expected for the lower heating time (due to poor signal-to-noise ratio), the apparent dependency of thermal diffusivity on heating time, evident for 50-100 seconds of microwave illumination, was not expected since thermal diffusivity is an intrinsic property. This apparent dependency is attributed to the temporal dependency of the temperature of the heat source (RAM) that results from the continuous heating approach. While this temperature dependency is not observed in Eq. (1), the fundamental conduction heat transfer equation does include a dependency on temperature difference ΔT (shown as T_2-T_1, below) and is defined as the following [16]:

$$Q = kA\frac{T_2 - T_1}{L} = \alpha\rho C_p A\frac{T_2 - T_1}{L} \tag{4}$$

where ρ is density, C_p is specific heat, A is the area of heat transfer, T_2 is the temperature of the back side of the material, T_1 is the temperature at the inspection surface (front side), and L is the thickness of the material. As it relates to the calculation done as part of the established (flash lamp) method, Eq. (1) was formulated with the assumption of an impulse-based heat source (i.e., the flash heat lamp) and hence a temporally known and fixed maximum ΔT results. However, when AMT is used, while there is a set/chosen maximum ΔT, this value depends on the heating time. As such, the measurement made by the proposed method has an inherent dependency on heating time which must be accounted for to reduce error. Additionally, this concept can be confirmed by considering the time at which the maximum temperature is reached. Heating times of 50-150 seconds of Table II (ignoring 25 seconds for poor signal-to-noise ratio) all reach their maximum temperature at close to the same time (within 2 seconds). This is indicative that the flow of heat is dependent on this temperature difference since a state of equilibrium was achieved at approximately the same point. Additionally, as the heating time is reduced (Fig. 12d), Region *A* (early flat slope) is less evident (i.e., low signal-to-noise ratio), indicating that this continuous heating scenario is not ideal for thermal diffusivity measurement as is currently calculated. As such, for this incident power level (50 W), a heating time range of 50-100 seconds is suggested for lossless materials to achieve a result with limited error.

The results for the lossy material, MUT-2 (i.e., Fig. 13 and Table 3), have relatively the same trend as those of MUT-1 (i.e., lowest error at 100 seconds of heating time). Overall, there is an increase in error, with the greatest error, once again, occurring at the lower heating times. This is an artifact of the RAM not absorbing enough electromagnetic energy at those times (i.e., low signal-to-noise ratio). The results from MUT-2 indicate that, for a 50 W AMT system, 100-150 seconds of electromagnetic illumination must be used to achieve a calculated thermal diffusivity with a reasonable expected error for a lossy material. However, once again, if a precise measurement is needed, another method (i.e., the established approach) is recommended when characterizing lossy materials.



(a) (b) (c) (d)

Fig. 13. Normalized AMT thermal diffusivity measurements of MUT-2 for heating times of: 150 seconds (a), 100 seconds (b), 50 seconds (c), and 25 seconds (d).

Table 3: Thermal diffusivity and error for MUT-2

Heating Time (s)	$t_{1/2}$ ***(s)***	***Thermal Diffusivity*** (mm^2/s)	***Error (%)***
150	216	0.1486	9.39
100	183	0.1729	5.43
50	169	0.1872	14.15
25	233	0.1358	17.20

IV. CONCLUSION

Active microwave thermography (AMT) is relatively new NDT&E technique that has been considered for thermal materials characterization of out-of-plane thermal diffusivity. As traditional measurement approaches for this parameter require a two-sided measurement, AMT is proposed as a single-sided alternative. This approach has been shown, via simulation and measurement, as a viable option for measurement of low loss materials if they are backed by an absorbing material. For materials with electromagnetic loss, this approach is still viable, albeit with a larger error (due to the inherent volumetric heating that takes place of the material in question). The results also indicate that, for a 50 W AMT system, heating time ranges vary dependent on material (i.e., 50-100 seconds for lossless and 100-150 seconds for lossy) is a necessary parameter to consider when utilizing this approach to achieve minimal error. Future works will include investigation of the conductive heat source as it relates to the calculation of thermal diffusivity and the impact of the continual heating that occurs during the proposed AMT-based approach.

ACKNOWLEDGEMENT

This work was partially supported by the Kummer Innovation and Entrepreneurship Doctoral Fellowship at Missouri University of Science and Technology and a U.S. Air Force SBIR Topic entitled "SBIR-Phase II: Nondestructive Evaluation of Composite Substrates below Thick Top Coat Materials" (AF183-041 SBIR Phase II). Additionally, the authors would like to thank Dr. Steven M. Shepard and his team of Thermal Wave Imaging, Inc. for conducting measurements on the rubber samples and providing their thermal diffusivities by the established approach.

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