Advanced Susceptors for Microwave Heating of Energetic Materials

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ABSTRACT

Trinitrotoluene (TNT) like many monomolecular organic explosives is transparent to microwave energy. This study examines the influence of carbon additives to TNT purposefully selected to absorb microwave energy and enable heating throughout the composite. Five carbon additives with different shapes are analyzed including carbon nanotubes, spherical powder, diamond nanoparticles, graphene nano-flakes, and graphite micron-flakes. Each was added to TNT at a constant 1 wt. % concentration then subjected to 1.7 GHz of microwave energy for up to one minute. In-situ two-dimensional transient temperature is measured using a high-resolution high-speed infrared (IR) camera. ANSYS high frequency structural simulator (HFSS) software simulated power absorption for each additive. Simulations predict tubes absorb more energy but experimentally flakes induce melting of the TNT faster. Further analysis of additive connectivity through the matrix suggests that inter-particle connectivity plays a strong role in enhancing heat transfer upon microwave attenuation; and flakes show the greatest inter-connectivity. Engineering composite materials with optimized additives could lead to advances in microwave technologies.

KEY WORDS

Microwave heating, powder compacts, susceptors, particle connectivity, particle shape, advanced energetic composites

INTRODUCTION

The interaction of electromagnetic energy with explosives is a relatively new area of research. In 2006 a patent showed that high explosives are nearly transparent to microwave energy but adding materials that readily absorb microwave energy (i.e., susceptors) can spur ignition [1]. Susceptors are additives that, in small concentration, attenuate microwave energy enabling improved heating throughout the composite [2]. Specifically, HMX mixed with carbon nanotubes (1 wt. %) ignited with 7.5 J at an average rate of 750 W for 10 ms [3]. To raise the same mass of neat HMX to an autoignition temperature of 473 K requires significantly more energy (about 110 J) for a longer duration (i.e., 150 ms) [3]. Advances in modeling software also enable electromagnetic properties to be better understood for energetic materials like HMX [3].

Susceptors such as graphite and aluminum particles were added to 1,3,5 trinitrotoluene (TNT) and exposed to 3.3 GHz microwave frequency for 120 seconds with energy fields varying from 164 to 168 W [4]. Graphite was shown to decompose TNT but aluminum (Al) particles did not work well in attenuating electromagnetic energy and showed very little temperature increase. Results also showed an optimum particle dispersion and concentration that effectively couples microwave energy [4]. Specifically, clusters of high susceptor concentration did not exhibit temperatures as high as regions of sparsely concentrated susceptors [4].

For enhanced reactivity, additives to explosives are usually metallic fuel particles that contribute to the energy released upon combustion [5]. But metals and even semiconductors such as carbon have only recently gained attention in the microwave literature [1]. This is because metals and semiconductors do not induce internal electric fields but rather the electric charge remains localized at the metal surface [1]. Consequently, reflection rather than absorption of the electromagnetic field prevents volumetric heating; this is especially true for bulk metals [6-8]. However, as recent as 1999, Roy et al. [9] introduced the first publication of metal powder heating from microwave coupling. In powder form, manifestation of the electric field at the surface takes on a unique dimensional affect, characterized by the skin depth (d). The skin depth is defined [10] as the distance into a material at which the incident power drops to 36.8% of the surface value and is mathematically expressed as **Eq. (1)**.

$$d = \sqrt{\frac{\rho}{\pi f \mu_0 \mu'}} \quad (1)$$

In **Eq. (1)** ρ is the resistivity of the material, f is the frequency of the alternating magnetic field, μ_0 is the permeability of free space ($=4\pi \times 10^{-7}$ H/m), and μ' is the magnetic permeability. For metals, the skin depth varies from 0.1 to 10 microns [9]. In this way, microwave heating is effective for powders with average particle diameter less than the skin depth [8]. With this understanding, microwave sintering studies that previously focused on ceramic susceptors, could now be extended to metal semiconductor and alloy powders as well as other applications [7-14]. Using metallic susceptors in neat explosives may also provide a safe means to dispose of explosive waste by de-linking the explosive component via microwave heating [1].

This study examined the influence of size and shape of the susceptor for attenuating microwave energy when combined with 1, 3, 5 TNT. Various sizes and shapes of carbon susceptors were selected and combined with TNT in a constant volume concentration. These experiments were performed in an electromagnetic exposure chamber using a 1.7 GHz frequency for up to one minute. *In-situ* two-dimensional transient temperature was measured using a high resolution high speed infrared (IR) camera. ANSYS high frequency structural simulator (HFSS) software was also used to simulate power absorption for the susceptor structures. A simple heat transfer analysis was then applied to model temperature for singular structures based on simulated power results.

EXPERIMENTAL

Materials

A base material of 1, 3, 5 trinitrotoluene (TNT) flakes was combined with one of five different carbon-based susceptors that included nanotubes, spherical powder, diamond nanopowder, graphene nano-flakes, and graphite micron-flakes. Images of the shape and morphology of each susceptor are shown in **Fig. 1**. **Table 1** summarizes material properties as well as supplier information.

Figure 1. Images from TEM Analysis for each carbon susceptor. Carbon nanotube (CNT) and spherical powder (SP) are abbreviated. Length scales are identified for each TEM image.

Table 1 List of materials with shape description, density, dimensions, and supplier. Shape and dimensions from TEM analysis. Density from supplier.

Material	Description	Density (g/cm ³)	Dimensions	Supplier
Trinitrotoloune	Flakes	1.654	Various	Texas Tech University
Carbon Nanotubes (CNT)	Multi-walled nano-tubes	1.350	3-20 nm OD, 1-3 nm ID, 0.1-10 μ m length	Alfa Aesar
Spherical Powder (SP)	Amorphous glassy spherical powder	1.450	3 μ m average diameter	Alfa Aesar
Diamond Nanoparticles	Nanoparticle spheres	3.100	4 nm average diameter	SkySpring Nanomaterials Inc.
Graphene	Nano-flake. Rectangular, nano-thickness	2.000	2 nm thickness, 550 nm lateral size	Graphene Supermarket
Graphite	Micron-flakes. Rectangular, micron-thickness	2.250	$\leq 44 \mu$ m	Alfa Aesar

A 1 wt. % concentration of each susceptor was added to a fixed volume of TNT flakes by physically dry mixing powders with a spatula until the dispersion quality appeared uniform. In this way, the susceptors are randomly aligned within the TNT matrix. The powder mixture was then cold pressed into a cylindrical composite measuring 12.6 mm diameter and 1.7 mm thickness. **Figure 2** shows photographs of each TNT + susceptor composite after being pressed. Three samples per TNT + susceptor were prepared for repeatability and a total of 15 composites were analyzed.

Figure 2. Photographs of each TNT composite with 1 wt. % susceptor after being pressed: A) CNT; B) SP; C) Diamond; D) Graphene; and, E) Graphite. The ruler provides scaling in each image.

Electromagnetic Exposure Chamber

An electromagnetic exposure chamber (EEC) exposed the composites to microwave energy and a high speed IR camera recorded the two-dimensional transient temperature profile on the exposed surface of the composites in-situ; the system is detailed in **Fig. 3**. In the EEC, microwaves are produced using a microwave amplifier and are transmitted into a waveguide via coaxial cables. The interior of the waveguide is made of brass and acts as a conduit for electromagnetic radiation. The waveguide is a WR430 model, with a frequency range of 1.70 to 2.60 GHz, and has a closed end where the microwave transmitter is located. The other end is open but has an aluminum mesh attachment designed to reflect the impeding microwaves and limit radiation leakage. The mesh has a thickness of 0.46 mm and mesh spacing of 1.12 m to protect the user from stray radiation which is continuously monitored using an electromagnetic frequency meter. Each composite is fitted into a polytetrafluoroethylene (PTFE) sample holder

specifically used for its transparency-like property to microwave energy. At 1.7 GHz, the location of the maximum electric field is located about 7.6 cm into the waveguide from the open end and is where the sample is positioned. A signal generator connects to the microwave amplifier that splits to a power meter and waveguide via coaxial cables. The signal generator sets the frequency, the amplifier transmits the forward power to the splitter, and the power meter reads forward and reverse power measurements from the waveguide.

Figure 3 Electromagnetic exposure chamber with: WR 430 Waveguide, Al mesh, IR camera, PTFE Holder, and TNT compact. Coaxial cables connect to an amplifier, signal generator, and power meter that are not shown in the figure.

Infrared Imaging Diagnostics

A FLIR SC8303 infrared camera positioned directly in front of the waveguide records two-dimensional transient thermal images. The infrared camera operates in the mid-wavelength region that spans a band of wavelengths from 3-5 μm . The camera is aligned to view the sample

that is placed 30.5 cm directly from the end of the waveguide. The viewing area of both the sample and holder is set at a 640 X 360 pixel window frame size. The integration time is set to 2.1 ms with an acquisition rate of 15 frames per second. That is: 230,400 discrete temperature measurements are made throughout the field of view every 2.1 ms. Emissivity for each sample is determined by referencing a known emissive source and then calibrated into the infrared camera. The infrared camera recorded for over 60 seconds while each composite is exposed to microwave energy. Stray microwave radiation is measured using an electromagnetic frequency (EMF) meter and did not exceed the FCC regulated amount of 5 mW/cm².

ANSYS HFSS Simulations

To compliment experimental results, microwave simulations were performed using ANSYS HFSS software. This software simulated the dissipated power (in Watts) by varying the structure or shape of the carbon susceptor. Three shapes were simulated as flakes, tubes, and spheres. The vessel for these shapes was a simulated theoretical waveguide with boundary conditions applied to the top and bottom, and sides which were perfectly magnetic and electric boundary conditions, respectively. The software did not account for the thermal behavior such that the simulations are used as an estimate for microwave energy absorption. Therefore, an additional heat transfer analysis was performed using a semi-infinite solid model [17] to relate simulated power to transient temperature. This analysis can then be compared with the experimental temperature measurements.

Laser Flash Analysis for Particle Connectivity

Comparison of experimental and simulated results provoked further investigation about the influence of susceptor thermal properties on the TNT matrix and particle interconnectivity

was considered. A modified Hashin-Shtrikman (HS) model [18] was applied and assumed a homogenous composite consisting of a matrix (i.e., TNT) with varied filler concentration (i.e., susceptor). If the matrix thermal conductivity is less than the susceptor ($\lambda_M < \lambda_P$) the composite thermal conductivity (λ_c) is the HS lower boundary condition, λ^{HS-} , shown by **Eq. (4)** and includes the volume fraction of spherical particles x_P .

$$\lambda_c = \lambda^{HS-} = \lambda_M \left[\frac{2\lambda_M + \lambda_P - 2x_P(\lambda_M - \lambda_P)}{2\lambda_M + \lambda_P + x_P(\lambda_M - \lambda_P)} \right] \quad (4)$$

However, if the matrix thermal conductivity is greater than the susceptor ($\lambda_M > \lambda_P$) then (λ_c) shown in **Eq. (5)** is the HS upper boundary condition λ^{HS+} that includes the matrix volume fraction, x_M instead.

$$\lambda_c = \lambda^{HS+} = \lambda_P \left[\frac{2\lambda_P + \lambda_M - 2x_M(\lambda_P - \lambda_M)}{2\lambda_P + \lambda_M + x_M(\lambda_P - \lambda_M)} \right] \quad (5)$$

The volume fractions in **Eq. (4)** and **(5)** were determined by dividing the volume of the susceptor or TNT by the total volume of the composite. The interconnectivity (X) from the HS model is shown in **Eq. (6)** where the measured thermal conductivity of the composite (matrix + particles) $\lambda_{measured}$ is required [19, 29].

$$X = \frac{\lambda_{measured} - \lambda^{HS-}}{\lambda^{HS+} - \lambda^{HS-}} \quad (6)$$

The thermal conductivities of pure TNT and TNT + susceptor composites were measured using a NETZSCH Laser Flash Analysis (LFA) 447 NanoFlash® analyzer. Samples examined in the LFA 447 were identical to those prepared and used in the microwave setup as previously described.

RESULTS AND DISCUSSION

During microwave heating, four out of five of the composites attenuated microwave energy and exhibited volumetric heating; furthermore, two composites experienced melting between 25 and 40 seconds. Thermal images for each composite are shown in **Fig. 4** after 60 seconds of microwave heating. Carbon nanotubes (CNT) and graphene produced melting of TNT during microwave exposure while the diamond nanoparticles did not attenuate energy (i.e., resulted in no thermal heating behavior). Interestingly spheres and graphite produce fairly symmetric temperature distributions while CNT and graphene show hot spots throughout the 60 seconds of microwave exposure. The hot spots produce TNT melting followed by removal of liquid TNT from the field of view. In this way, the average temperature within the field of view is erroneous after TNT melting.

Figure 4 Thermal imaging using the FLIR SC8303 infrared camera for TNT with carbon susceptors of: A) CNT B) SP C) Diamond D) Graphene and E) Graphite. Color scale from “hot” (red) to “cool” (blue) is shown along the side.

Data for the average temperature for each composite is plotted as a function of time in **Fig. 5**. Composite melting for CNT occurred at 40 s while melting for graphene occurred at 25 s.

Figure 5. Transient temperature data obtained from the FLIR SC8303 infrared camera for all TNT + susceptor composites with melting points identified for carbon nanotubes (CNT) and graphene. Note SP = spherical particles and Diamond indicates diamond particles. Peak temperature values are displayed for each curve.

To further explore the two carbon susceptors that melted TNT, the heating rate for CNT and graphene flakes is determined by curve fitting **Fig. 5** up to melting then taking the derivative with respect to time; shown in **Fig. 6**. Graphene shows about a 40% increase in heating rate from

start to finish compared to CNT. The irregular sharp edges of the graphene flakes may attenuate microwave energy better than symmetric tube-like structures of CNT (see **Fig. 1**).

Figure 6, Heating rates for CNT and graphene up to TNT melting obtained from Figure 5 by taking the time derivative of the respective curves.

Another interesting finding is the influence of spherical diameter on heating. The diamond nanoparticles that are on average 4 nm diameter show negligible temperature change (i.e., from Fig. 4) whereas the spherical particles (i.e., 3 micron diameter) demonstrate a linear growth in temperature, albeit less than the other structures. This is interesting because it is in paradox to the trends in microwave heating behavior cited in the literature with other materials. Generally, simulations and experiments on materials such as tungsten (Mishra et al [20]) and copper (Mondal et al [21]) show that as the particle size decreases, heating resulting from microwave absorption increases, respectively. Mishra et al. [20] examined tungsten particles ranging from 12 to 3 microns diameter and showed heating rate increased by over 200% with decreased particle size. Mondal et al. [21] examined copper particles from 383 to 6 microns in diameter and noted steady state temperature increased with decreased particle size from nearly

800 to 1000 °C. While these studies did not investigate nano-scale materials, the trend suggests increased heating with decreased particle size. However, results here suggest there may be a limit to optimizing microwave heating by decreasing particle diameter. **Figure 5** clearly shows that larger spheres (3 micron diameter) produce higher temperatures than nano-spheres (4 nm diameter). Further studies are needed to confirm the influence of spherical particle diameter on heating.

Electromagnetic Simulations

Table 3 lists the dimensions, number of particles, and simulated dissipated power for the flakes, tubes, and sphere geometries simulated in a theoretical waveguide. The flakes differ only in their thickness: graphene is 10 nm thick while graphite is 100 nm thick. The tubes were simulated for two configurations: one aligned parallel to the electric field and the other aligned perpendicular to the electric field. The number of particles simulated was determined from the varied densities in an effort to maintain a constant weight percent similar to the experiments performed. ANSYS simulations show that power dissipated for both the flakes and tubes aligned parallel to the electric field are three orders of magnitude greater than that of spheres and tubes aligned perpendicular to the electric field.

Table 3 ANSYS HFSS simulation results for tubes, flakes, and spheres for 1.7 GHz; note l = length, r = radius and w = width. Note also that parallel denotes that the particle is aligned parallel to the electric field while perpendicular denotes that the particle is aligned perpendicular to the electric field.

Shape	Dimension (nm)	Number of Particles	Dissipated Power (W)
Tubes – Parallel	$l=500$ $r=10$	16	9.69×10^{-08}
Tubes - Perpendicular	$l=500$ $r=10$	16	1.83×10^{-11}
Spheres	$r=3000$	2	7.75×10^{-12}
Graphene Flakes	$l=500$ $w=500$ $t=10$	10	9.08×10^{-08}
Graphite Flakes	$l=500$ $w=500$ $t=100$	2	2.83×10^{-08}

This simulation corresponds well with the experimental results in that tubes and flakes (i.e., CNT, graphene, and graphite) exhibited greater temperatures than spheres. When the tubes are aligned with the electric field the dissipated power is higher than when the tubes are oriented perpendicular to the electric field. Experimentally however, the orientation of the CNT are randomly distributed. The flakes in Table 3 differ by thickness. Graphene induces higher heating rates and melting in the TNT whereas graphite (an order of magnitude thicker) shows 68 % decrease in power dissipation and results in an average of 20% decrease in temperature. The simulation results correspond well with the thermal observations.

Heat Transfer Model

A basic analytical heat transfer model aided analyzing the heating behavior for each susceptor at the interface of the susceptor and TNT. This model assumes a semi-infinite solid approximation with a constant heat flux [17] to estimate interface heating between susceptor and TNT. The transient temperature solution for this model is shown in **Eq. (2)** [17].

$$T(x, t) - T_i = \frac{2q_0''}{k} \left(\frac{\alpha t}{\pi} \right)^{\frac{1}{2}} \exp\left(\frac{-x^2}{4\alpha t}\right) - \frac{q_0'' x}{k} \operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha t}}\right) \quad (2)$$

Here the temperature $T(x, t)$ is a function of the distance (x) from the susceptor particle surface and time (t) as well as thermal properties of the material such as the thermal conductivity (k) and thermal diffusivity (α). The heat flux (q_0'') is determined from the power dissipation simulations (**Table 3**) divided by the surface area of each susceptor and assuming the initial temperature (T_i) is ambient. At the susceptor-TNT interface (i.e., $x = 0$), **Eq. (2)** reduces to **Eq. (3)**.

$$T(0, t) = T_i + \frac{2q_0''}{k} \left(\frac{\alpha t}{\pi} \right)^{\frac{1}{2}} \quad (3)$$

Experimental values for the thermal conductivity of multi-walled CNT vary widely [22-26] from 3000 W/m·K at room temperature [22] to 17 W/m·K [23] and in between [24, 25]. Xie et al. [26] measured the thermal diffusivity for multi-walled CNT using a laser flash technique at a temperature range of -55-200 °C and found that the thermal diffusivity exhibited no obvious change from 75-200 °C. At room temperature the thermal diffusivity was $4.6 \times 10^{-4} \text{ m}^2/\text{s}$ with a mean thermal conductivity of 750 W/m·K and is the value used here. The thermal conductivity for spherical powder was provided by the supplier, and thermal diffusivity is estimated from measurements by Shinzato et al. as $5.91 \times 10^{-3} \text{ m}^2/\text{s}$. [27]. Desai et al. [28] measured thermal properties of three different carbon flakes that varied in size corresponding to 180, 300, and 600 μm average flake size. The analysis here used their results for the smallest flakes and corresponds to a thermal conductivity of 52 W/m·K and diffusivity of $4.54 \times 10^{-5} \text{ m}^2/\text{s}$ [28]. Note that the graphene thermal properties were provided by the supplier and the diamond nanoparticle thermal properties were not examined due to no temperature change as seen from Fig. 4. All thermal properties are summarized in Table 4.

Table 4 Thermal properties of materials used in heat transfer analysis. N/A represents data not required for analysis.

Susceptor	Thermal Conductivity $k \text{ (W/m} \cdot \text{K)}$	Thermal Diffusivity $\alpha \text{ (m}^2/\text{s)}$	Normalized Temperature
SP	4.6	5.91×10^{-3} [27]	1.3×10^{-02}
CNT	750 [26]	4.6×10^{-4} [26]	1.0
Diamond	N/A	N/A	0
Graphene	3000	9.08×10^{-8}	2.4×10^{-02}
Graphite	52 [28]	4.54×10^{-5} [28]	1.0×10^{-01}

Results from the heat transfer analysis are summarized in the last column of **Table 4**. The normalized temperature is the temperature for each carbon susceptor after achieving peak temperature divided by the maximum temperature that occurred for CNT. Values for SP, diamond, and graphite are listed for ($t > 60s$) while CNT and graphene are reported before melting ($t < t_{melt}$). From **Eq. (3)** using the thermal properties from **Table 4** as well as power dissipation and number of particles from **Table 3**, results show that CNT exhibits the highest normalized temperature followed by graphene, graphite, SP, and then diamond nanoparticles. This analysis follows a similar trend to the ANSYS HFSS simulations shown in **Table 3**. The heat transfer analysis shows CNT produces the highest interface temperatures, but experimentally graphene was shown to produce TNT melting prior to CNT. This difference may be because graphene flake structures promote greater interconnectivity throughout the TNT matrix compared to the tube-like structure of CNT. Greater interconnectivity may enhance heating that promotes melting, but interconnectivity is not accounted for in the simulations and heat transfer model.

Susceptor Interconnectivity Analysis

Table 5 lists the calculated thermal conductivities of each susceptor λ_p and the measured thermal conductivities for each TNT + susceptor composite $\lambda_{meas.}$ using the LFA 447. The HS lower and upper bound thermal conductivities from **Eq. (5)** and **(6)** and volume fractions are listed in **Table 5**. The value for the measured thermal conductivity for pure TNT was 1.55 W/mK. Interconnectivity is normalized against the highest value calculated, which is for graphene, in order to better represent the relative interconnectivity of each susceptor.

Table 5 List of parameters used to calculate the normalized interconnectivity X_N based on the volume fraction for each susceptor (x_P), and TNT (x_M), thermal conductivities measured from the LFA 447 for each susceptor λ_P and TNT + susceptor $\lambda_{meas.}$, and the HS lower and upper bound thermal conductivities(λ^{HS-} and λ^{HS+})

Susceptor	x_P	x_M	λ_P (W/m•K)	λ^{HS-} (W/m•K)	$\lambda_{meas.}$ (W/m•K)	λ^{HS+} (W/m•K)	X_N
CNT	8.44E-03	0.804	2	0.158	0.172	0.421	0.0526
SP	9.76E-03	0.798	2	0.159	0.163	0.429	0.0160
Diamond Nanoparticles	5.17E-03	0.806	2	0.157	0.159	0.417	0.0079
Graphene	6.29E-03	0.7998	2	0.157	0.185	0.428	0.1023
Graphite	7.55E-03	0.8015	2	0.158	0.179	0.425	0.0792

The interconnectivity results from **Table 5** show that the flake structures, graphene and graphite, have a higher interconnectivity than CNT and spherical particles. This would further support that while thermal conductivity plays a large part in heat transfer, the interconnectivity of susceptors within the TNT matrix also contribute to the overall heat transfer and explains that graphene exhibits melting prior to CNT because particle interconnectivity promotes improved heat transfer upon susceptor attenuation of microwave energy.

CONCLUSIONS

Microwave heating of a monomolecular explosive, TNT, was investigated as a function of five different carbon-based susceptors: nanotubes, micron-spheres, nano-spheres, and flakes of graphene and graphite. Experimental results confirm shape plays a significant role in susceptor heating. The spherical particles experienced little to no heating while the tube and flake particles induced melting of the TNT matrix. Simulations using ANSYS HFSS compliment the experimental results by showing that rectangular and tube like structures attenuate maximum energy. The heat transfer analysis further suggests that the thermal conductivity of the susceptor

is not the contributing factor for enhancing heat transfer of the composite, but instead particle interconnectivity within the TNT matrix significantly influences energy buildup. Nano-thickness flake structures (i.e., graphene) produce greater interconnectivity that enhances the overall heat transfer of the composite and induces melting of the TNT when exposed to microwave energy. Using susceptors to induce melting in explosives exposed to microwave energy could be a new approach for de-linking explosive components for demilitarization applications.

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REFERENCES

- [1] Perry W. L., Son S., & Asay B. W. Microwave Heating of Energetic Materials, US Patent No. 20060011083 (2006).
- [2] Heuguet, R., Marinel, S., Thuault, A. & Badev, A. Effects of the susceptor dielectric properties on the microwave sintering of alumina. *J. Am. Ceram. Soc.* **96**, 3728–3736 (2013).
- [3] Duque, A. L. & Perry, W. L. Microwave-Induced Heating of HMX for Decomposition Kinetic Analysis. *Materials Research Society Proc.* **1405**, (2012).
- [4] Crane, C. A., Pantoya, M. L. & Weeks, B. L. Utilizing Microwave Susceptors to Visualize Hot-Spots in Trinitrotoluene. *J. Microwave Power & Electromagnetic Energy.* **48**, 5–12 (2014).

- [5] Crane, C. A., Pantoya, M. L. & Weeks, B. L. Investigating the trade-offs of microwave susceptors in energetic composites: Microwave heating versus combustion performance. *J. Appl. Phys.* **115**, 2–7 (2014).
- [6] Gupta, M. & Eugene, W. W. L. *Microwaves and Metals*. 1st ed, Singapore *John Wiley & Sons*. 35-36 (2007)
- [7] Ma, J., Diehl, J. F., Johnson, E. J., Martin, K. R., Miskovsky, N. M., Smith, C. T., Weisel, G. J., Weiss, B. L., & Zimmerman, D. T. Systematic study of microwave absorption, heating, and microstructure evolution of porous copper powder metal compacts. *J. Appl. Phys.* **101**, (2007).
- [8] Kaur, R. & Probert, S. D. Multi-purpose Mathematical Model for Electromagnetic- Heating Processes. **44**, 337–386 (1993.)
- [9] Roy R., Agrawal D.K., Cheng J.P., & Gedevanishvili S. Full sintering of powdered-metal bodies in a microwave field, *Nature* **399**, 668-670 (1999)
- [6] Gupta, M. & Eugene, W. W. L. *Microwaves and Metals*. 1st ed, Singapore *John Wiley & Sons*. 29-33 (2007)
- [11] Agrawal, D., Cheng, J., Seegopaul, P., & Gao, L. Grain growth control in microwave sintering of ultrafine WC-Co composite Powder Compacts. *Powder Metallurgy*. **43**, 15-16, (2000)
- [12] Rödiger, K., Dreyer, K., Gerdes, T. & Willert-Porada, M. Microwave sintering of hardmetals. *Int. J. Refract. Met. Hard Mater.* **16**, 409–416 (1998).

- [13] Takayama S., Link G., Miksch S., Sato M., Ichikawa J., Thumm M., Millimetre wave effects on sintering behaviour of metal powder compacts, *Powder Metallurgy*, **49**, 274-280 (2006)
- [14] Wong, W. L. E. & Gupta, M. Development of Mg/Cu nanocomposites using microwave assisted rapid sintering. *Compos. Sci. Technol.* **67**, 1541–1552 (2007).
- [15] Bykov Y. V., Rybakov K. I., & Semenov V. E. High-Temperature Microwave Processing of Materials, *J. Phys. D: Appl. Phys*, **34**, R55–75 (2001)
- [16] Saremi-Yarahmadi, S., Vaidhyanathan, B. & Wijayantha, K. G. U. Microwave-assisted low temperature fabrication of nanostructured α -Fe₂O₃ electrodes for solar-driven hydrogen generation. *Int. J. Hydrogen Energy*. **35**, 10155–10165 (2010).
- [17] Incropera F. P., Dewitt D. P., Bergman T. L., Lavine A. S., Fundamentals of Heat and Mass Transfer, *John Wiley & Sons*, 123-129(2006)
- [18] Hashin, Z. & Shtrikman, A. A variational approach to the theory of the effective magnetic permeability of multiphase material. *J. Appl. Phys.* **33**, 3125–3131 (1962)
- [19] Weidenfeller B., Höfer M., & Schilling F. R., Thermal Conductivity, thermal diffusivity, and specific heat capacity of particle filled polypropylene. *Composites Part A: Applied Science and Manufacturing*. **35**, 423-429 (2004)
- [20] Mishra P., Sethi G., & Upadhyaya A., Modeling of Microwave Heating of Particulate Metals. *Metallurgical and Materials Transactions B*. **37**, 839-845 (2006)
- [21] Mondal, A., Shukla, A., Upadhyaya, A. & Agrawal, D. Effect of porosity and particle size on microwave heating of copper. *Sci. Sinter*. **42**, 169–182 (2010).

- [22] Kim, P., Shi, L., Majumdar, A., & McEuen, P. L. Thermal Transport Measurements of Individual Multiwalled Nanotubes, *Physics Review Letters*. **87**, 215502 (2001)
- [23] Dames, C., Chen, S., Harris, C. T., Huang, J. Y., Ren, Z. F., Dresselhaus, M. S., & Chen, G. A hot-wire probe for thermal measurements of nanowires and nanotubes inside a transmission electron microscope. *Rev. Sci. Instrum.* **78**, 1–13 (2007).
- [24] Mäkilä, J., Halonen, N., Toth, G., Sági, A., Kukovecz, Á., Kónya, Z., Jantunen, H., Mikkola, J., & Kordas, K. Thermal diffusivity of aligned multi-walled carbon nanotubes measured by the flash method. *Phys. Status Solidi B*. **248**, 2508–2511 (2011)
- [25] Aliev, A. E., Lima, M. H., Silverman, E. M., & Baughman, R. H. Thermal conductivity of multi-walled carbon nanotube sheets: radiation losses and quenching of phonon modes, *Nanotechnology*, **21**, 035709 (2010)
- [26] Xie, H., Cai, A., & Wang, X. Thermal diffusivity and conductivity of multiwalled carbon nanotube arrays. *Physics Letters A*. **369**, 120–123 (2007)
- [27] Shinzato, K. & Baba, T. A Laser Flash Apparatus For Thermal Diffusivity And Specific Heat Capacity Measurements, *J. Thermal Analysis and Calorimetry*. **64**, 413-422 (2001)
- [28] Desai, S. & Njuguna, J. Thermal properties of natural graphite flake composites. *International Review of Mechanical Engineering*. **6**, 923-926 (2012)
- [29] Schilling F. R., Partzsch G. M., Quantifying partial melt portion in the crust beneath the Central Andes and the Tibetan Plateau. *Physics and Chemistry of the Earth*. **26**, 239–246 (2001)