https://doi.org/10.1051/e3sconf/202457606003

Degradation of Carbon/Phenolic Composite Materials for Spacecraft Structure Material

Mahfud Ibadi[1], *David* Natanael Vicarneltor[1], *Muhamad* Hananuputra Setianto[1], *Muhammad* Johan Rifai[1], *Purwoko* Purwoko[1], *Herry* Purnomo[1], and *Yudan* Whulanza[2*]

[1]Aeronautics and Spaces Research Organization, National Research and Innovation Agency (BRIN), West Java, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, West Java, Indonesia

Abstract. Due to their ability to be tailored in terms of strength, stiffness, and density, composite materials are a valuable commodity in the aerospace sector. But composite materials also deteriorate with time, just like other materials do, particularly in abrasive conditions like space. Thermal degradation brought on by abrupt temperature changes in the aircraft environment, which can result in dimensional changes, cracking, and even decomposition of composite materials, are degradation issues that can influence composite materials in aerospace applications. In this study, thermogravimetric analysis (TGA) of carbon/phenolic composites, as a fiber using carbon fiber (Kyoto - carbon) with plain weave type and as a matrix using ARMC-551-RN phenolic resin. Furthermore, the test method refers to the ASTM E1131-08 Standard. Thermogravimetric Compositional Analysis Test Method. Ultimately, engineers hope to improve spacecraft design, reliability, and safety in severe space missions by using TGA analysis to understand the thermal characteristics and stability of carbon/phenolic composite materials utilized in spacecraft components.

1 Introduction

Human activities in the aerospace environment have positive and negative impacts on the earth condition [1]. When it comes to scientific research, telecommunications, and remote sensing—which involves taking high-resolution pictures of the Earth's surface—satellites, which are artificial space objects, are essential [2]. Some examples of the detrimental impacts of human aerospace activity include the buildup of space debris, which includes spacecraft, the danger of Earth collisions from objects that survive atmospheric re-entry, and the adverse impact on amateur and professional astronomical observations [3].

The structure of a spacecraft requires several characteristics, including mechanical, ablation, thermal, and dimensional stability [4]. To prevent spacecraft failure in the high-temperature aerobic environment, those features were necessary as effective thermal protection [5]. Carbon/phenolic composites that met those criteria could be considered as

---

[*] Corresponding author: yudan.whulanza@ui.ac.id

materials for spacecraft [6]. Before being used in spacecraft, these materials' thermal load-related degradation must be thoroughly investigated [7].

Studies on ARMC-551-RN phenolic resin have been done in the past, however, this kind of resin can only be used as an adhesive at very high temperatures. [8−11]. Therefore, the most significant outcome of this research is an attempt to investigate the resistance of ARMC-551-RN phenolic resin to thermal degradation at elevated temperatures as a matrix when utilized in carbon/phenolic composites. Using the outcomes as a guide while implementing the spacecraft's structural elements.

2 Materials and Methods

The research on the thermal degrading properties of carbon/phenolic composite materials was carried out in three main stages, there are material selection, carbon/phenolic composite manufacture, and thermogravimetric analysis. The matrix of the composite was made of phenolic-based resin, and the reinforcing was made of plain-woven carbon fiber. Hand lay-up was used in the composite fabrication procedure, which was then followed by press molding and curing. Thermogravimetric analysis was employed to ascertain the carbon/phenolic composite's heat degradation profile. The research's experimental diagram is shown in Figure 1.

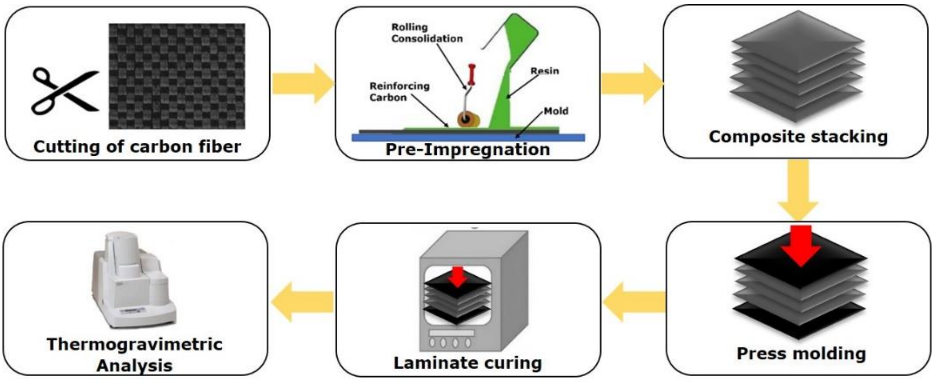

Fig. 1. Diagram of Experimental Design.

2.1 Material Selections

The carbon fiber type we used for our research was called Kyoto-carbon, and it was obtained from Kyoto Carbon Corp. in Indonesia. It has a thickness of 0.27 mm and a plain weave pattern of 3K × 3K. In Table 1, mechanical parameters are displayed.

Table 1. Technical Data Sheet Carbon Fiber [12].

Tensile Strength	3310 MPa
Tensile Modulus	240 GPa
Strain	1.6 %
Density	1.78 g/cm3
Gramatur	220 gsm

The matrix used in this research is ARMC-551-RN resin supplied by Aremco, which has the properties shown in Table 2. With carbon filler, ARMC-551-RN is a resin that can be applied up to 2985°C and is based on phenolic material as a binder [9]. At an elevated temperature, the ARMC-551-RN resin was cured.

Table 2. Technical Data Sheet ARMC-551-RN Resin.

Filler	Carbon
Binder	Phenolic
Tensile Strength	9.82 MPa
Density at 25°C	1.25 g/cm3
Viscosity at 25°C	75000 cP

2.2 Manufacturing techniques

To construct C/ARMC Composite Panels, ten carbon fiber layers must be stacked with all orientations at the same angle, either 90° or 0°. Due to the extremely high viscosity of ARMC-551-RN resin (75000 cP; Table 2), the manual layup is necessary because the resin cannot be removed by a machine vacuum. The curing process was applied to the resin ARMC-551-RN. There were three steps to the process: first, it was left out in the open for one to four hours at room temperature; second, it was heated for four hours at 130°C in an oven; and third, it was heated for two hours at 260°C.

2.3 Thermogravimetric Analysis (TGA)

The Shimadzu DTG-60H was utilized to conduct the TGA test. This instrument's method of operation involves detecting variations in sample mass as temperature rises. The TGA test findings can be used to study material deterioration caused by temperature variations. The ASTM E1181 standards-recommended parameters are used for TGA testing [13]. The temperature range for the test was room temperature to 850°C, and the gas replacement for conditioning was done at 600°C. Nitrogen is the inert gas utilized in this experiment. Ten degrees Celsius are heated each minute in this TGA test.

3 Results and Discussion

TGA can be used to study the thermal stability (strength of a material at a given temperature), oxidative stability (the rate of oxygen absorption in a material), and constitutive properties (e.g. fillers, polymer resins, solvents) of a sample. In addition, the addition/decrease in weight in the sample is related to various factors. In general, an increase in sample mass is associated with adsorption or oxidation, while a decrease in sample mass is associated with decomposition, desorption, dehydration, solvation, or volatilization [14, 15]. The thermogravimetric analysis uses heat to force reactions and physical changes in materials. TGA provides quantitative measurements of mass changes in materials associated with thermal transitions and degradations. The TGA records changes in the mass of dehydration, decomposition, and oxidation of the sample as a function of time and temperature [16].

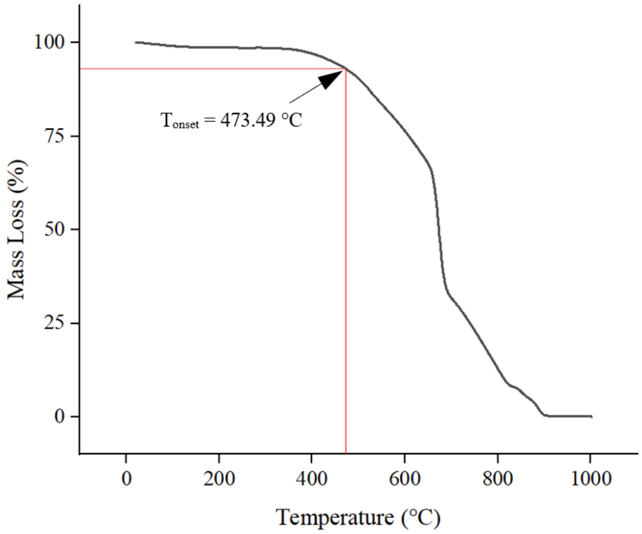

Fig. 2. Carbon/phenolic Composite Thermogravimetric Analysis Result's Curve.

The carbon/phenolic composite material's thermogravimetric analysis curve is shown in Figure 2. The T_{onset} of the carbon/phenolic composite material may be found in this curve. The temperature at which decomposition starts is known as the T_{onset}. T_{onset} is defined as the temperature at which a sample loses 7% of its starting weight since samples might vary in the amount of water that has been adsorbed and in the pace at which they lose weight [17]. And carbon/phenolic composite T_{onset} at 473.49°C. Additionally, the ASTM E1131–08 Standard Test Method for Compositional Analysis by Thermogravimetry [13] is cited in the test method. This method offers a general technical explanation of Thermogravimetry Analysis and helps identify residue, highly volatile matter, medium volatile matter, and combustible material, all of which are listed in Table 3.

Phenolic matrix degraded at higher temperatures compared to epoxy. T_{onset} of carbon/epoxy composite was at 365.63°C [12]. On the other hand, carbon/phenolic composite has T_{onset} at 473.49°C. Based on the thermogravimetric test, carbon/phenolic material has a bigger potential to be applied as a spacecraft structure compared to other aerospace application matrix materials that have been reported, such as epoxy DER-331 at 300°C, Poly methyl methacrylate (PMMA) at 243°C, Polybenzimidazole (PBI) at 471°C, and Polyurethane (PU) at 335°C [18, 19]. Higher T_{onset} of carbon/phenolic material showed that this material can withstand better with thermal load.

A highly volatile substance degrades at a rate of 1.216% when it comes to highly volatile matter carbon/phenolic composite. Examples of extremely volatile substances include moisture, additives, leftover solvents, and other components with a low boiling point (200°C or less). Moreover, the acceptable temperature range for volatile matter mediums like oil content and polymer degradation products is 200 to 550°C, and the material degradation that takes place in carbon/phenolic composites is 15.171%. The next combustible material phase is composed of materials that may decompose at 750°C; in this phase, the material degradation that occurs for carbon/phenolic composite materials is 60.451%. Residues are the remains of materials that do not readily oxidize. This might be because of the material's composition, which can include filler, metal components, or inert reinforcing elements. residue on phenolic/carbon materials, yielding 6.631%.

Table 3. Analysis of Thermogravimetric Results of carbon/phenolic Composite.

Characteristics	**Degradation (%)**
Highly Volatile	1.216
Medium Volatile	15.171
Combustible	60.451
Residue at 850°C	6,631

The inclusion of materials in the composite can significantly slow down the decomposition rate, with the primary function of forming and retaining charcoal on the composite surface, according to the TGA results. This also holds for resins, where adding particulate matter can lessen the composite's ablation [20].

From Table 3, carbon/phenolic showed better stability when exposed to high temperatures, unlike carbon/epoxy. Carbon/phenolic is a more explosive substance that can survive at higher temperatures [12]. When facing high temperatures, carbon/phenolic material will stay better than carbon/epoxy because it has more mass that can give structural strength.

4 Conclusion

The Thermal Gravimetric Analysis (TGA) results offer valuable insights into the thermal stability, oxidative stability, and constitutive properties of carbon/phenolic composites. This material demonstrates superior thermal stability to carbon/epoxy composites, boasting a higher initial decomposition temperature (T_{onset}) of 473.49°C. Consequently, the study concludes that carbon/phenolic composites exhibit superior thermal stability and are better suited for spacecraft structures when compared to carbon/epoxy composites. The ability of these materials to endure high temperatures and retain structural integrity makes them a compelling choice for aerospace applications.

The author would like to thank the Rumah Program Research Organization for Aeronautics and Space 2024 for their support with contract number 27/III.1/HK/2024 and the Seed Funding Grant from the Faculty of Engineering, University of Indonesia 2024.

References

1. K. J. Gaston, K. Anderson, J. D. Shutler, R. J. Brewin, X. Yan, Environmental impacts of increasing numbers of artificial space objects. Front. in Eco. and the Env. **21**, 289–296 (2023). https://doi.org/10.1002/fee.2624
2. A. Sharma et al., Onboard compression and preprocessing methods for leo satellite imagery: a review, in Prooceding in AI for Biomedical Instrumentation, Electronics and Computing, CRC Press, 2024
3. L. Miraux, Environmental limits to the space sector’s growth. Sci. of The Tot. Envi. **806**, 150862 (2022). https://doi.org/10.1016/j.scitotenv.2021.150862

4. W. Yuan, Y. Wang, Z. Luo, F. Chen, H. Li, T. Zhao, Improved performances of sibcn powders modified phenolic resins-carbon fiber composites. Processes. **9**, 6 (2021). https://doi.org/10.3390/pr9060955
5. R. K. Chinnaraj, Y. C. Kim, S. M. Choi, Arc-jet tests of carbon–phenolic-based ablative materials for spacecraft heat shield applications. Materials. **16**, 10 (2023). https://doi.org/10.3390/ma16103717
6. S. Ahmad, S. Ali, M. Salman, A. H. Baluch, A comparative study on the effect of carbon-based and ceramic additives on the properties of fiber reinforced polymer matrix composites for high temperature applications. Cer. Int. **47**, 33956–33971 (2021). https://doi.org/10.1016/j.ceramint.2021.08.356
7. A. A. Adem, H. Panjiar, B. S. S. Daniel, The effect of nanocarbon inclusion on mechanical, tribological, and thermal properties of phenolic resin-based composites: an overview. Eng. Rep. **6**, 4 (2024). https://doi.org/10.1002/eng2.12861
8. L. Paglia et al., Manufacturing, thermochemical characterization and ablative performance evaluation of carbon-phenolic ablative material with nano-Al2O3 addition. Poly. Deg. and Stab. **169**, 108979 (2019). https://doi.org/10.1016/j.polymdegradstab.2019.108979
9. R. Harris, Q. Leland, J. Du, L. Chow, Characterization of paraffin-graphite foam and paraffin-aluminum foam thermal energy storage systems, in Proceeding 9th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, California: American Institute of Aeronautics and Astronautics, San Francisco, Juny (2006)
10. S. D. Pierre des Ammbrois et al., Adhesive joining of zerodur–cfrp–zerodur sandwich structures for aerospace applications. Macromol. Mater. Eng. **305**, 2000464 (2020). https://doi.org/10.1002/mame.202000464
11. V. Casalegno, M. Salvo, S. Rizzo, L. Goglio, O. Damiano, M. Ferraris, Joining of carbon fibre reinforced polymer to al-si alloy for space applications. Int. Jour. of Adh. and Adhes. **82**, 146–152 (2018). https://doi.org/10.1016/j.ijadhadh.2018.01.009
12. M. Ibadi, H. Purnomo, D. N. Vicarneltor, H. B. Wibowo, M. H. Setianto, Y. Whulanza, Investigation of thermomechanical analysis of carbon/epoxy composite for spacecraft structure material. JSM. **53**, 691–704 (2024). https://doi.org/10.17576/jsm-2024-5303-16
13. ASTM E1131 – 08, Standard test method for compositional analysis by thermogravimetry. American Society for Testing Materials, 2010
14. L. G. M. de Souza, E. J. da Silva, L. G. V. M. de Souza, Obtaining and characterizing a polyester resin and cement powder composites, Mat. Res. **23**, 5 (2020). https://doi.org/10.1590/1980-5373-mr-2018-0894
15. N. A. Raof, R. Yunus, U. Rashid, N. Azis, Z. Yaakub, Effect of molecular structure on oxidative degradation of ester based transformer oil. Tri. Int. **140**, 105852 (2019). https://doi.org/10.1016/j.triboint.2019.105852
16. D. Bücheler, A. Kaiser, F. Henning, Using thermogravimetric analysis to determine carbon fiber weight percentage of fiber-reinforced plastics. Comp. Part B: Eng. **106**, 218–223 (2016). https://doi.org/10.1016/j.compositesb.2016.09.028
17. C. N. Zárate, M. I. Aranguren, M. M. Reboredo, Thermal degradation of a phenolic resin, vegetable fibers, and derived composites. J. Appl. Polym. Sci. **107**, 2977–2985 (2008). https://doi.org/10.1002/app.27455
18. E. M. Chistyakov, I. V. Terekhov, A. V. Shapagin, S. N. Filatov, V. P. Chuev, Curing of epoxy resin der-331 by hexakis (4-acetamidophenoxy) cyclotriphosphazene and

properties of the prepared composition. Polymers. **11**, 7 (2019). https://doi.org/10.3390/polym11071191

19. G. Barra, L. Guadagno, M. Raimondo, M. G. Santonicola, E. Toto, S. Vecchio Ciprioti, A comprehensive review on the thermal stability assessment of polymers and composites for aeronautics and space applications. Polymers. **15**, 18 (2023). https://doi.org/10.3390/polym15183786
20. A. Shaheryar, S. Khan, H. Qaiser, A. A. Khurram, T. Subhani, Mechanical and thermal properties of hybrid carbon fibre–phenolic matrix composites containing graphene nanoplatelets and graphite powder. Plas. Rub. and Comp. **46**, 431–441 (2017). https://doi.org/10.1080/14658011.2017.1385177