Solid Freeform Fabrication 2024: Proceedings of the 35th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Tensile and Fatigue Analysis of Functionally Graded Materials with Varying Concentrations Manufactured Using Material Extrusion

Suhas Alkunte[1], Ismail Fidan[2], Vivekanand Naikwadi[3], Shamil Gudavasov[3]

[1]Department of Engineering Technology, Old Dominion University, Norfolk, VA 23529, USA, salkunte@odu.edu
[2]Department of Manufacturing and Engineering Technology, Tennessee Tech University, Cookeville, TN 38505, USA, ifidan@tntech.edu
[3]Additive Manufacturing Research and Innovation Laboratory, Tennessee Tech University, Cookeville, TN 38505, USA, sgudavaso42@tntech.edu, vanaikwadi42@tntech.edu

Abstract

This study employs material extrusion (MEX) technique, specifically a multi-material single extrusion system, to fabricate functionally graded materials (FGM) by blending PLA and TPU materials. This process introduces a gradient transition aimed at reinforcing the material interface. An array of concentration patterns, spanning from 20% to 80% by volume of FGM, undergoes systematic evaluation under both tensile and fatigue loading conditions. During fabrication, meticulous control is exercised over experimental parameters, encompassing stress level, stress ratio, and frequency. The characterization process entails a comparative analysis of the FGM interfaces. Results reveal a noteworthy enhancement in interface strength, irrespective of gradient alterations in material concentrations. This enhancement is particularly pronounced during the transition from softer to harder material constituents. The primary objective of this study is twofold: to elucidate the behavior of the material under tension-tension loading scenarios and to provide comprehensive insights into the intricacies of FGM interfaces.

Keywords: functionally graded materials, tensile, fatigue, additive manufacturing, material extrusion

Introduction

Over the past two decades, Additive Manufacturing (AM) has revolutionized the manufacturing industry [1–4]. Significant advancements in AM techniques have broadened the scope of material possibilities, allowing for the production of parts with varying physical [5], thermal [6], and chemical properties. Furthermore, these innovations have enabled the creation of complex multi- material structures [7], showcasing intricate geometries previously unattainable through traditional manufacturing methods. The study of FGMs using AM techniques represents a compelling frontier. FGMs are characterized by their gradual variations in composition and structure, offering considerable potential across diverse industries, particularly in energy systems [8]. FGMs play a pivotal role in optimizing mechanical, thermal, and electrical properties, thereby enhancing performance and reliability in sectors spanning aerospace to electronics [9, 10]. Their capability to mitigate stress concentrations, enhance thermal management, and enable the seamless integration of materials with disparate properties contributes significantly to sustainability initiatives by optimizing resource efficiency and promoting the use of alternative or recycled materials [11]. Currently, these properties of FGMs are predicted using various methodologies such as machine learning approach [12, 13] and analytical methods [14, 15]. Figure 1 illustrates a schematic view detailing the process description of the MEX process.

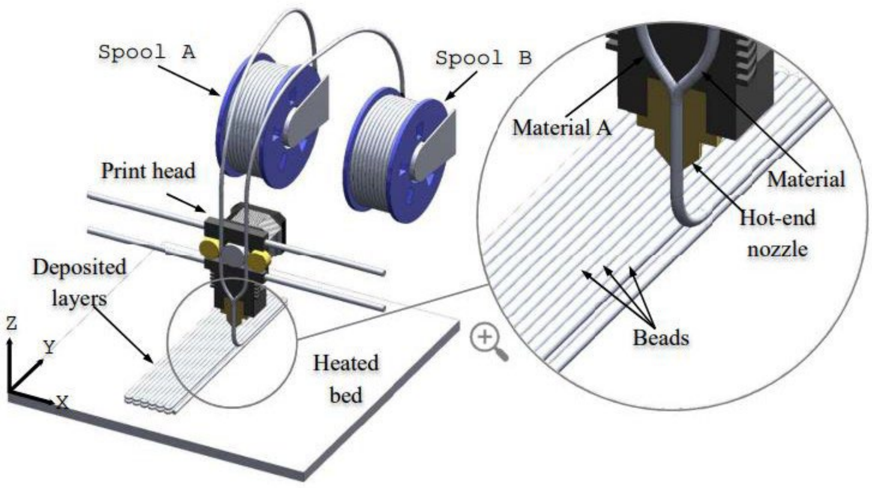

Figure 1: Schematic representation of MEX process

A few studies have been conducted to design, manufacture, and characterize the behavior of FGMs with varying compositions. Su et al.[16] fabricated Inconel-steel FGMs using laser additive manufacturing (LMD), transitioning from 100% 316 L stainless steel to 100% Inconel 718 with composition gradients of 5%, 10%, and 20%. The microstructure, phase evolution, and mechanical properties of these components were analyzed using microscopy, energy dispersive spectroscopy, X-ray diffraction, micro-indentation, and tensile tests. The FGM with a 10% composition gradient exhibited the highest tensile strength and elongation among all gradients studied. Moreover, Chen et al. [17] employed powder metallurgy technique of spark plasma sintering to fabricate FGMs consisting of AlN ceramic and metal. Various graded compositions were designed according to the Power function, and the influence of microstructure on the mechanical properties of AlN/Mo FGMs was analyzed. Results indicated that an increased content of hard metal network in the graded layer correlates with higher bending and shear strength of the AlN/Mo FGMs. Additionally, Hasanov et al. [18] investigated the design, fabrication, and characterization of FGMs produced using the MEX process. The study focused on Polycarbonate (PC)/Acrylonitrile Butadiene Styrene (ABS) FGM parts, which were mechanically characterized in three different printing orientations (XY, YZ, XZ). Additionally, the mechanical behavior of the interface regions between different materials was analyzed. A data-driven linear regression model was used to assess varying concentration levels of the PC/ABS blend. ANOVA results indicated that the volume fraction of the PC/ABS blend and the printing temperature significantly affect Young's modulus. Similar kind of study conducted by Bobibbo et al. [19] fabricated FGMs with varying elemental compositions using the directed energy deposition technique. A sample graded from Ti-6Al-4V to Invar 36 was selected due to the distinct thermal and mechanical properties of these materials. The local microstructure, elemental composition, mechanical properties, and phase composition of the FGM were experimentally characterized. Results demonstrated that the experimental computational approach described for characterizing FGMs can enhance the understanding and design of other

FGMs. Banthia et al. [20] examined copper-based functionally graded coatings (FGCs) under corrosive conditions in 3.5 wt.% NaCl solution and sliding wear tests. The Cu-Cu-SiC FGC consists of three copper layers, each 12 µm thick, and two Cu-SiC nanocomposite layers, also 12 µm thick, with SiC content varying from 2 to 7 vol%. Results show that the Cu-Cu-SiC FGC demonstrates enhanced corrosion resistance and superior wear resistance under high loads compared to the Cu FGC.

In this study, a multi-material single extrusion system was utilized to fabricate composite structures of FGMs, incorporating a gradient transition to enhance the robustness of material interfaces. These structures were meticulously designed, fabricated, and systematically analyzed. The primary objective of this analysis was to gain comprehensive insights into the material's behavior under tension-tension loading scenarios.

Materials and Methods

To investigate the properties of amorphous polymers with diverse material characteristics, a range of materials were employed in this study. Specifically, amorphous polymers such as Thermoplastic Polyurethane (TPU) and Polylactic Acid (PLA) were utilized due to their unique attributes, including tailored mechanical properties, processability, biocompatibility, sustainability, biodegradability, and enhanced adhesion and compatibility. These FGMs have potential applications in robotic grippers and prosthetic socket designs. The parameters used for printing the specimens are detailed in Table 1.

Table 1: Printing parameters of FGM specimens

Parameters	Values
Nozzle temperature (°C)	210
Bed temperature (°C)	60
Infill density (%)	100
Infill pattern	Line (0/90)
Layer width (mm)	0.35
Layer height (mm)	0.2
Printing speed (mm/sec)	15

Specimen fabrication and preparation

For the preparation of fatigue test specimens, ASTM standard E606M [21] was followed. The dimensions of the prepared specimens are illustrated in Figure 2. Each specimen measures 135 mm in length, 20 mm in width, and 5 mm in thickness, with a curvature radius at the gauge length of 10 mm. A single nozzle dual-material 3D printer called ZMorph™ [22] is used to fabricate multi-material structures. The printer operates on the principle of the MEX technique and allows for the simultaneous extrusion of two different materials through a single nozzle. The filaments used had a diameter of 1.75 mm, with PLA being transparent in color and TPU being black.

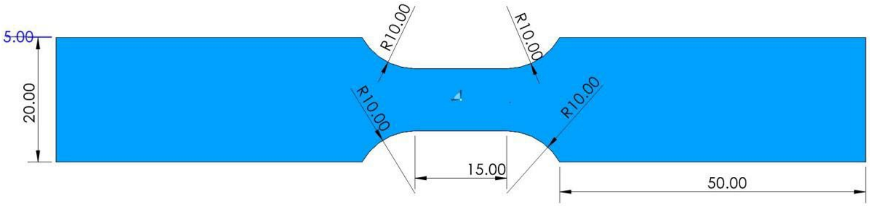

Figure 2: Dimensional details of the fatigue test specimen as per E606M

In the present study, six different compositions of TPU and PLA were used to create the specimens as shown in Figure 3, with each composition printed three times, resulting in a total of 18 fabricated specimens. The first specimen was composed entirely of 100% TPU. The second specimen consisted of 80% TPU and 20% PLA. The third specimen had a composition of 60% TPU and 40% PLA. The fourth specimen contained 40% TPU and 60% PLA. The fifth specimen comprised 20% TPU and 80% PLA. The sixth and final specimen was made entirely of 100% PLA. This gradient transition aimed to enhance the robustness of the material interface.

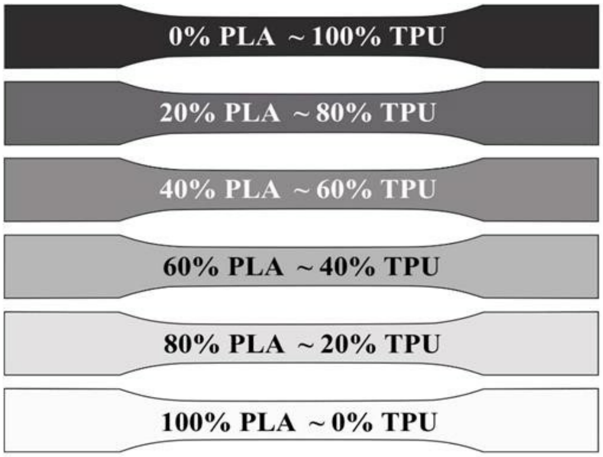

Figure 3:Varying concentrations of the TPU and PLA materials

Experimental Setup

In this study, uniaxial tensile and fatigue tests were performed on plastic specimens using a Testresources 810E4 [23] load frame equipped with a 15 kN load cell, in accordance with the ASTM E606M standard. The Newton Testware [24] interface was used to control and input all testing parameters, including frequency, amplitude, and average load. A PID controller was utilized to maintain the desired stress level throughout the tests. The experimental test setup is illustrated in Figure 4.

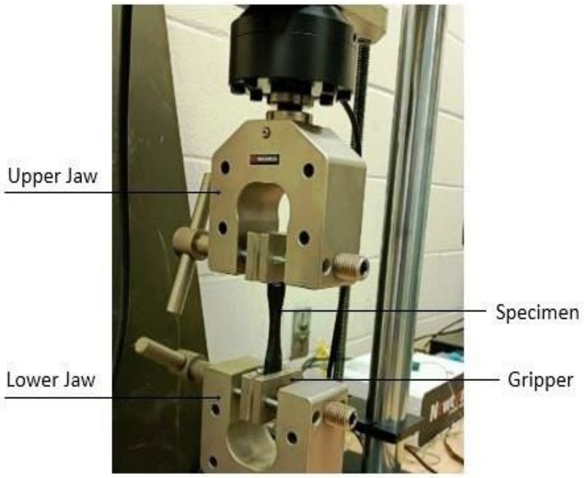

Figure 4: Test setup

Results and Discussions

Analysis of Tensile Behavior

The focus of these tests encompasses the progressive modulation of material properties, spanning a spectrum extending from pristine TPU to PLA. Figure 5 presents the outcomes of the tensile testing conducted at different concentrations. The graphical representation distinctly illustrates a progressive upsurge in both the strength and stiffness attributes of the material, as the transition unfolds from neat TPU to PLA, in the XY plane. At a full concentration of TPU, the observed tensile strength is measured at 12 MPa. When the TPU is combined with PLA in an 80% TPU and 20% PLA mixture, the tensile strength increases to 18 MPa. In a composition of 60% TPU and 40% PLA, the tensile strength further escalates to 25 MPa. As the proportion shifts to 40% TPU and 60% PLA, the tensile strength reaches 33 MPa. A blend consisting of 20% TPU and 80% PLA yields a tensile strength of 38 MPa. Finally, when the concentration is exclusively 100% PLA, the tensile strength reaches its highest value at 46 MPa.

These findings demonstrate a systematic correlation between material composition and resulting tensile strength properties. The systematic variation of PLA concentration within the TPU matrix exhibits a noteworthy trend, demonstrating that as the proportion of PLA is increased, the tensile strength consistently rises. This observation underscores the reinforcing effect of PLA on TPU, which leads to enhanced tensile properties. The increased tensile strength with higher PLA concentrations is indicative of the synergistic behavior between the two materials, showcasing the potential for tailored material compositions to achieve desired mechanical characteristics in the resulting composite.

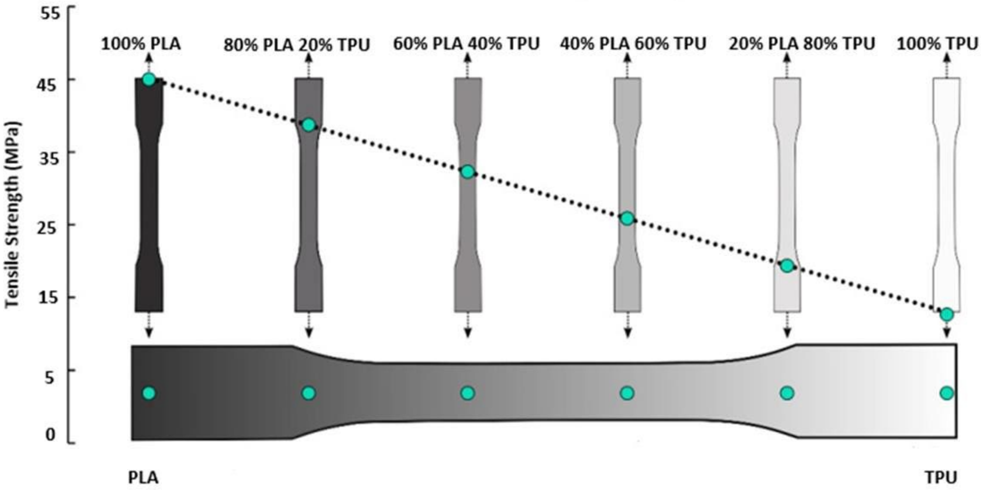

Figure 5: Load vs Displacement curve of FGM with varying compositions

This becomes particularly valuable in the context of AM, specifically MEX processes, where FGM components can be intricately fabricated on the XY plane. This breakthrough holds the transformative promise for diverse applications, such as aerospace, automotive, and biomedical fields, where components with varying strengths and stiffness profiles can be strategically designed to optimize performance, minimize weight, and enhance structural integrity. As a result, these findings contribute significantly to the advancement of customizable and high-performance material systems, ultimately fostering innovation and practical implementation of FGMs in various engineering sectors.

Analysis of Fatigue Behavior

The analysis of fatigue behavior across different concentrations of TPU and PLA in FGMs is of paramount significance for optimizing design, predicting durability, tailoring performance, and advancing material innovation. The provided data in Figure 6 presents a comprehensive insight into the fatigue behavior of varying concentration of FGMs composed of TPU and PLA. This analysis bears substantial significance for the design, durability, and practical utilization of such composite materials in engineering applications. The observed trend in the stress-number of cycles relationship across different compositions offers valuable findings. The fatigue behavior exhibited by FGMs is intriguing, showcasing a distinctive response as the ratio of PLA to TPU changes as shown in Figure 6. In the case of an 80% PLA and 20% TPU composition, the FGM demonstrates a reduced stress threshold and fewer cycles to failure, highlighting a compromise between tensile strength and fatigue resistance. This trend becomes more pronounced up on the PLA content decreases. In the 60% PLA and 40% TPU configuration, the fatigue performance is notably reduced, implying that the heightened brittleness of PLA plays a dominant role. A similar observation is made for the 40% PLA and 60% TPU composition, further emphasizing the impact of material proportionality on fatigue properties. Contrastingly, as the proportion of TPU is increased, the fatigue endurance found improved. The FGM consisting of 20% PLA and 80% TPU demonstrates a considerable extension in the number of cycles to failure, indicating the advantageous ductility and energy absorption capabilities of TPU. Moreover, the 100% TPU configuration showcases the highest fatigue resistance, corroborating the intrinsic resilience of TPU.

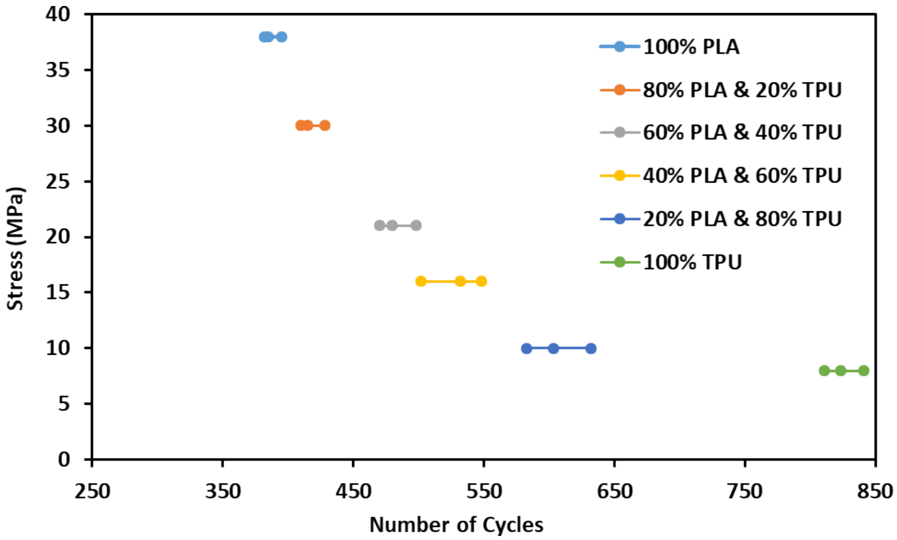

Figure 6: Fatigue analysis of FGM with varying compositions

These outcomes resonate with the intricate interplay between material composition and fatigue characteristics. They provide invaluable insights for engineering design, allowing for the strategic selection of material ratios based on the desired fatigue performance. As such, this research underscores the importance of tailoring FGM compositions to achieve optimal mechanical behavior, contributing to the advancement of reliable and high-performance materials.

Conclusion

This article provides a concise overview of an experimental study conducted on FGM specimens with varying concentrations, manufactured using the MEX process. The study focuses on characterizing the tensile properties and fatigue behavior. The main findings of this research are summarized as follows:

- The study indicates a progressive increase in strength from TPU to PLA, suggesting that MEX-produced FGMs offer customizable properties.
- Highlights include the potential for precise control of mechanical properties in FGM components to meet specific design requirements.
- The study establishes a clear correlation between the composition of TPU and PLA in FGMs and their fatigue behavior, resulting in significant variations in the stress-cycle relationships.
- Material composition greatly impacts fatigue performance; increased PLA content compromises tensile strength, while higher TPU proportions enhance ductility and energy absorption capabilities.

Future works

The scope of the future studies is given below:

- Improving the software capabilities to design FGM with varying concentrations is needed.
- Understanding the fracture behavior of multi material interfaces under bending fatigue.
- Fatigue modelling and characterization.

Acknowledgment

The authors greatly acknowledge the support provided by the Center for Manufacturing Research, Mechanical Engineering and Manufacturing and Engineering Technology Department which enabled us to carry out the research work at Tennessee Tech University.

References

1. Hasanov S, Alkunte S, Rajeshirke M, et al (2021) Review on Additive Manufacturing of Multi-Material Parts: Progress and Challenges. Journal of Manufacturing and Materials Processing 2022, Vol 6, Page 4 6:4. https://doi.org/10.3390/JMMP6010004
2. Alshaikh M, Fidan AI, Ali MA, Fidan I (2023) Investigation of the Impact of Power Consumption, Surface Roughness, and Part Complexity in Stereolithography and Fused Filament Fabrication. The International Journal of Advanced Manufacturing Technology. https://doi.org/10.1007/s00170-023-11279-3
3. Fidan, I.; Imeri, A.; Gupta, A.; Hasanov, S.; Nasirov, A.; Elliott, A.; Alifui-Segbaya, F. The trends and challenges of fiber re-inforced additive manufacturing. Int. J. Adv. Manuf. Technol. 2019, 102, 1801–1818. https://doi.org/10.1007/S00170-018-03269-7
4. Gupta A, Fidan I, Hasanov S, Nasirov A (2020) Processing, mechanical characterization, and micrography of 3D-printed short carbon fiber reinforced polycarbonate polymer matrix composite material. International Journal of Advanced Manufacturing Technology 107:3185–3205. https://doi.org/10.1007/S00170-020-05195-Z/METRICS
5. Fidan, I.; Huseynov, O.; Ali, M.A.; Alkunte, S.; Rajeshirke, M.; Gupta, A.; Hasanov, S.; Tantawi, K.; Yasa, E.; Yilmaz, O.; et al. Recent Inventions in Additive Manufacturing: Holistic Review. Inventions 2023, 8, 103. https://doi.org/10.3390/inventions8040103
6. Huseynov O, Hasanov S, Fidan I (2023) Influence of the matrix material on the thermal properties of the short carbon fiber reinforced polymer composites manufactured by material extrusion. J Manuf Process 92:521–533. https://doi.org/10.1016/J.JMAPRO.2023.02.055
7. Alkunte S, Rajeshirke M, Fidan I, Hasanov S (2023) Performance evaluation of fatigue behavior in extrusion-based functionally graded materials. International Journal of Advanced Manufacturing Technology 128:863–875. https://doi.org/10.1007/S00170-023-11922-Z
8. S. Alkunte, I. Fidan, V. Naikwadi, S. Gudavasov, M Alshaikh Ali, S, Hasanov, M. cheepu, M, Mahmudov, Advancements and Challenges in Additively Manufactured Functionally Graded

Materials: A Comprehensive Review, J. Manuf. Mater. Process. 2024, 8(1), 23; https://doi.org/10.3390/jmmp8010023

9. Rajeshirke M, Alkunte S, Huseynov O, Fidan I (2023) Fatigue analysis of additively manufactured short carbon fiber-reinforced PETG Components. International Journal of Advanced Manufacturing Technology 1–18. https://doi.org/10.1007/S00170-023-12107-4/METRICS

10. Alkunte, S.; Fidan, I.; Hasanov, S. Experimental Analysis of Functionally Graded Materials produced by Fused Filament Fab-rication. In Proceedings of the 2022 International Solid Freeform Fabrication Symposium, Austin, TX, USA, 25–27 July 2022. https://doi.org/10.26153/tsw/44144. Accessed: October 3,2023

11. Fidan I, Naikwadi V, Alkunte S, et al (2024) Energy Efficiency in Additive Manufacturing: Condensed Review. Technologies 2024, Vol 12, Page 21 12:21. https://doi.org/10.3390/TECHNOLOGIES12020021

12. Alkunte S, Fidan I (2023) Machine Learning-Based Fatigue Life Prediction of Functionally Graded Materials Using Material Extrusion Technology. Journal of Composites Science 2023, Vol 7, Page 420 7:420. https://doi.org/10.3390/JCS7100420

13. Rajeshirke M, Alkunte S, Huseynov O, Fidan I Solid Freeform Fabrication 2023: Proceedings of the 34th Annual International Solid Freeform Fabrication Symposium-An Additive Manufacturing Conference Reviewed Paper

14. Alkunte S, Rajeshirke M, Huseynov O, Fidan I Fatigue Life Prediction of Functionally Graded TPU and PLA Components Produced by Material Extrusion

15. Hasanov S, Gupta A, Nasirov A, Fidan I (2020) Mechanical characterization of functionally graded materials produced by the fused filament fabrication process. J Manuf Process 58:923–935. https://doi.org/10.1016/j.jmapro.2020.09.011

16. Su Y, Chen B, Tan C, et al (2020) Influence of composition gradient variation on the microstructure and mechanical properties of 316 L/Inconel718 functionally graded material fabricated by laser additive manufacturing. J Mater Process Technol 283:116702. https://doi.org/10.1016/J.JMATPROTEC.2020.116702

17. Chen F, Jia M, She Y, et al (2020) Mechanical behavior of AlN/Mo functionally graded materials with various compositional structures. J Alloys Compd 816:152512. https://doi.org/10.1016/J.JALLCOM.2019.152512

18. Hasanov S, Gupta A, Nasirov A, Fidan I (2020) Mechanical characterization of functionally graded materials produced by the fused filament fabrication process. J Manuf Process 58:923–935. https://doi.org/10.1016/J.JMAPRO.2020.09.011

19. Bobbio LD, Otis RA, Borgonia JP, et al (2017) Additive manufacturing of a functionally graded material from Ti-6Al-4V to Invar: Experimental characterization and thermodynamic calculations. Acta Mater 127:133–142. https://doi.org/10.1016/J.ACTAMAT.2016.12.070

20. Banthia S, Sengupta S, Das S, Das K (2019) Cu, Cu-SiC functionally graded coating for protection against corrosion and wear. Surf Coat Technol 374:833–844. https://doi.org/10.1016/J.SURFCOAT.2019.06.050

21. E606/E606M Standard Test Method for Strain-Controlled Fatigue Testing. https://www.astm.org/e0606_e0606m-21.html. Accessed 17 Jun 2024

22. FAB | Zmorph S.A. https://zmorph3d.com/products/zmorph-fab/. Accessed 17 Jun 2024

23. 810E4-15 Dynamic & Fatigue Test Machines. https://www.testresources.net/test-machines/fatigue-test-machines/800-series/810e4-15. Accessed 17 Jun 2024

24. Newton Test Machine Controller. https://www.testresources.net/test-machines/newton-test-machine-controller/. Accessed 21 May 2023