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Experimental Analysis of Fatigue Crack Path for Strained Functionally Graded Materials

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Abstract: This paper experimentally discusses crack paths in strained Functionally graded materials under constant loading conditions and vibration fatigue. The objective is to synthesize the body of knowledge on the stability of FGM. The article presents the development, production, and characterization of multi-Al (aluminum), Ni (nickel), and Titanium alloys. FGM it was successfully modified using the powder metallurgical technique. Five-layer FGM samples frequently utilize (Al, Ni), on one end and (Al-Ni-Ti) on the first. FGM sample mechanical characteristics have been investigated using wear and Fatigue testing. The Al/Ni/Titanium FGM compact specimen approaches the yield stress and ultimate stress values, which is regarded as a significant improvement in mechanical qualities with less weight. The test findings are for a constant amplitude load fully reversed with zero mean stress. The stress life approach examined three samples' fatigue characteristics and natural frequency under random vibration.

Keywords: crack paths, FGM, Fatigue vibration.

1. Introduction

FGM is a novel Adaptive hybrid material with features that can be specific uses, transforming materials science. However, the remaining difficulties impede the achievement of this goal. In addition to the significant cost issue, additional obstacles include a need for more data obtained and This methodology can be used with approaches such as mass production adequately. More study is needed to create an appropriate database, including detailed characterization of Improved FGMs can be created through the use of models of prediction for more accurate process control. Completely automatic production lines can't function without a reliable feedback mechanism.; thus, substantial study is needed for real process control improvement. Functionally graded materials are classified using two different criteria. The first is based on material structure, while the second is based on the size of functionally graded materials. Functionally graded materials can be further separated into two primary classes depending on the material structure. FGM is both constantly and intermittently organized [1]. Continuous FGM is characterized by a constant gradient from one material to the next. However, a layered material gradient is given in the case of discontinuous FGM. FGMs are selected depending on the size of the substances used: thinner FGMs and bulky FGMs. Thin FGM could be to have relatively.

Powder metallurgy converts metal powders into usable technical compounds [2]. The primary advantage of PM is that it allows mass-creating components with high dimensional precision and mechanical qualities cost-effectively, which you require at a cheap cost and with minimal waste. A dynamic kinematic model to study the vibration response of multilayer FGM shell is a significant development of Carrera's ensure the effectiveness. Due to the excellent accuracy, the provided method could be used to assess multilayer shells, according to the researchers [3].

The conservation equations solution of the Levy form FGM geometrical shapes were obtained employing Donnell's and Sander's shells concepts under various boundary conditions. A frequency parameter clearly relates to the curvature proportion, according to the findings [4]. Researchers used millimeter-wave heating to prepare bulk multilayered scaled Ni- Al_2O_3 specimens to minimize cracks and layer delamination, the cross-sectional area of refined materials heated inside an inhomogeneous temperature distribution [1]. The Al-SiC FGM has indeed been created, significantly increasing strength properties [5].

The tensile test, which measures the material's stiffness, can determine the modulus of elasticity, stress values, ultimate elongation, and ultimate tensile strength. A material will distort when it's under stress. Elongation is the variation between the unloaded and loaded length. The idea of strain is employed for contrasting the lengthening of a material with its original, undeformed size [6-8].

The modeling of layered materials can be complicated by material defects such as pores or microcracks. These features should be incorporated into the model of the structure or element. Before the failure of any component, multi-site cracks are always present. Fractures. All of these cracks' fracture tip stress fields interact with one another, and this interaction causes one dominant gap to emerge, which ultimately causes the component to fail. Additionally, the presence of visible and microscopic flaws in the material causes failure [9, 10]. The lowest rate of Fatigue Crack Growth (FCG) depends on the rupture energy (T), which in turn depends on the strength of the weakest bonds and the molecular weight between the bonds. In contrast, the maximum rupture energy depends on the time, the degree of swelling, and the temperature [11].

This study examines lattice structures' suitability for vibration fatigue applications. It combines experimental and numerical methods to assess two lattice configurations: Face-Centered Cubic (FCC) and Diamond structures. Using finite element models, the study predicts fatigue life and damage under both resonant and random vibrations, offering valuable insights for lightweight component design [12].

Friction welding was used to join aluminum and magnesium bars. The interface was examined using microscopy and X-ray diffraction. Varying friction and forge pressure influenced intermetallic compound thickness. Increased pressure reduced compound thickness but prevented microcrack formation. Tensile strength reached 138 MPa, dependent on pressure [13].

Friction stir processing created an aluminum metal matrix with Al_2O_3 nanoparticles. Multiple FSP passes evened nanoparticle distribution, increasing hardness. Microstructure analysis showed 80% finer grains after two and three passes than the base metal. Tool speed and pass number greatly affected strength and surface hardness. Al_2O_3 nanoparticles increased UTS by 25% and average hardness by 46% [14].

2. Preparation of powder alloy

FGMs samples consist of five layers., the first of which has a thickness of 2 mm and was made from (75% Ni and 25% Al). The components of each layer (Ni 33.3%, Al 33.3%, and Ti 33.3%) are mixed in fixed proportions. Table 1 displays the amounts of Ni, Al, and Ti employed in this investigation at each concentration. Table 2 shows the percentage composition of the Al-Ni-Ti samples for FGM.

Table 1. *Powder Property Specifications*

Metal	Graine Size(μm)	Density (g/cm3)	Purity (%)	company
Aluminium	18.3	2.79	99	CDH
Nickle	9.922	8.9	99.8	METCO
Titanium	28	4.28	98	Changsha

Table 2. *Shows the Composition of Five Layers FGM*

Layer number	%Ni	%Al	% Ti	Thickness layer(mm)	Compound weight(gm)
1	65	35	0	2	1.147
2	25	25	50	2	1.09
3	50	25	25	2	1.088
4	55	25	20	2	1.17
5	33.3	33.3	33.3	2	0.98

Analysis of increasing pressing pressure, a development of compaction values shows how particle shapes and matrix stiffness affect the compression test. The preforms of greens are weighed to an accuracy of 0.001 g, and their dimensions are measured to an accuracy of 0.01 mm using a micrometer caliper. X-ray fluorescence XRF was used to thoroughly characterize the FGMs compound powder and evaluate the composition of its elements. The powder mixture was packed into a steel die and cold pressed in a uniaxial direction. Compaction pressures varied from 50 MPa to 800 MPa [15]. This study employed a range of compaction pressures to suppress the dynamic load characteristic. To quantify the compaction behavior of aluminum, the densification of metal particles during uniaxial compaction was considered.

3. Results and Discussions

Microstructure plays a significant role in determining the tribological characteristics of alloys. The primary determinants of sliding wear characteristics are the quantity, size, form, and type of phases in the microstructure. Wear tests were performed at room temperature for 5, 10, and 15 minutes with loads of 10, 15, and 20 N on an FGM, Al-Ni, and Ti sample. Figures 1-2 display the results of the wear testing. In addition, the natural frequency calculations used in the present investigation, which investigate fatigue caused by random vibrations, are covered here. The natural frequency characteristics of short beams generated by horizontally stacked composite (FGM) were investigated experimentally. Powder metallurgy is used to create beams that have different material properties across the longitudinal axis. Aluminum alloys, nickel, and Titanium are used in various weight fractions.

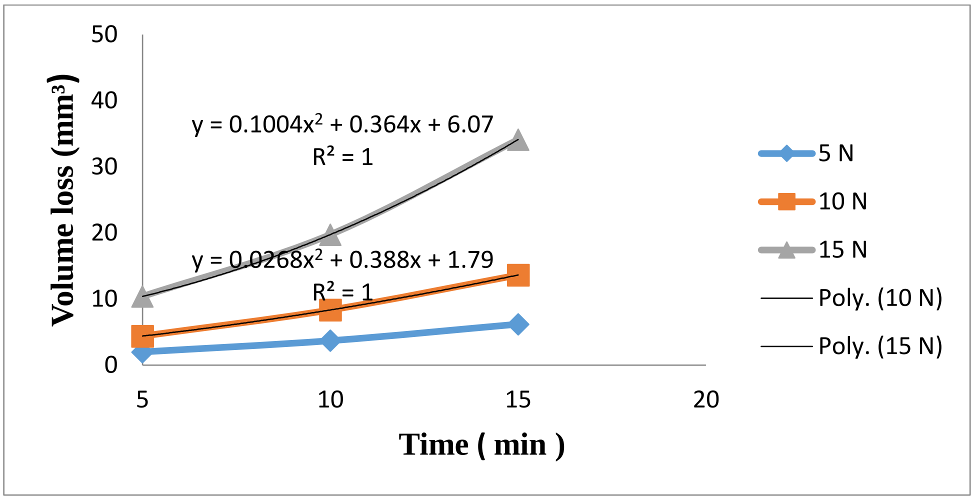

Figure 1: *First layer wear rate under 5, 10, and 15 N loads*

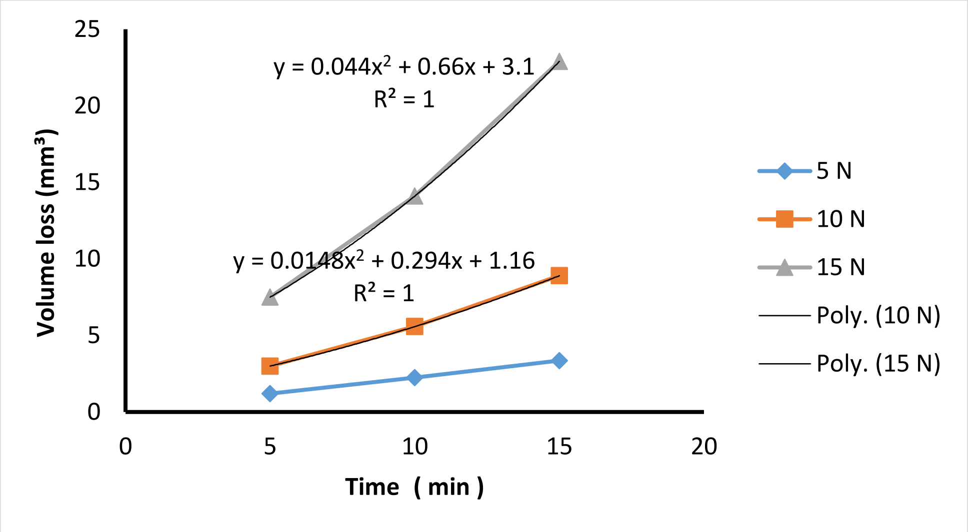

Figure 2: *Fifth layer wear rate under 5, 10, and 15 N loads*

The results analysis shows that when the applied load increases, the wear rate also increases. The friction between the sample surface and the rotating disc increases as the load increases. Furthermore, when the friction duration rises, the wear rate increases with time due to the continual loss of sample particles. Moreover, the constant loss of sample particles leads the wear rate to grow with time. as the friction duration increases. According to the statistics, the first layer had the highest wear rate compared to the other layers, measuring (6.0 mm^3) at (5 min) load duration and under (5 N) applied force. The fifth layer showed the lowest value. (1.7 mm^3). Figures (3,4 and 5) illustrate the FGMs sample's and each layer's wear rate at 5,10, and 15 min and under 5,10, and 15 N.

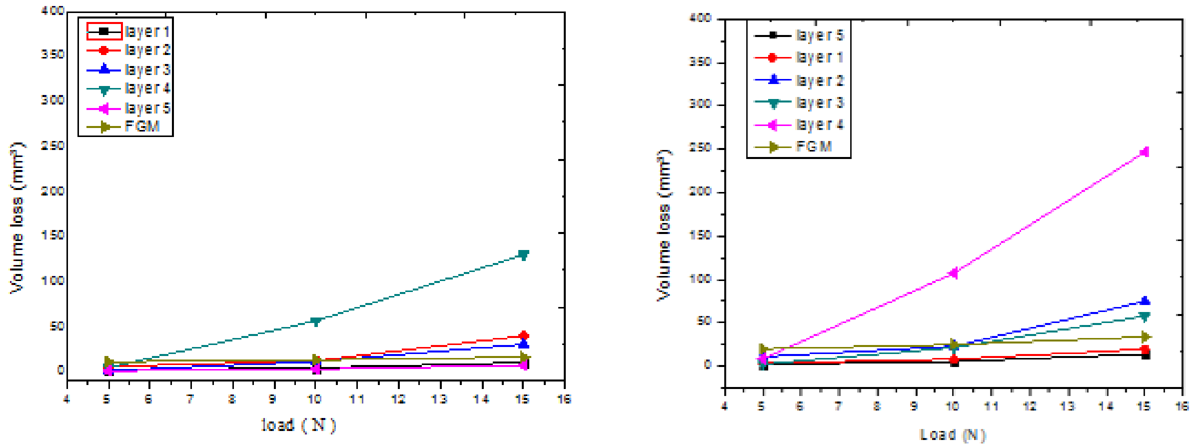

Figure (3-4): *FGMs sample wear rate for each layer at 5 and 10 min*

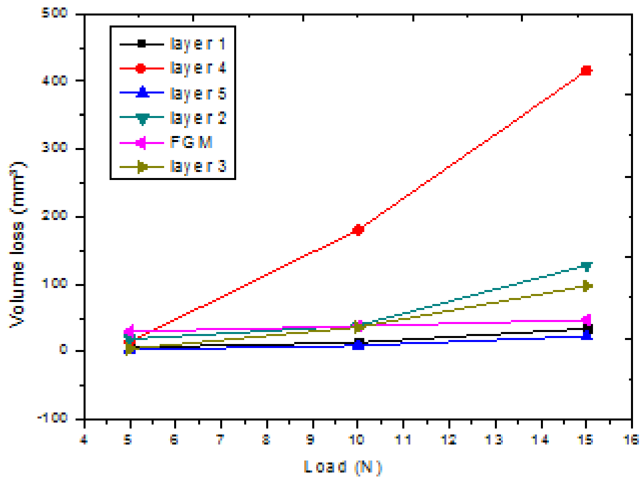

Figure (5): *FGMs sample wear rate for each layer at 15 min*

Modeling of layered materials can be complicated by Material defects such as pores or microcracks. These features should be incorporated into the model of the structure or part. A multi-crack and its path are always present before a component fails. All of these cracks' fracture tip stress fields interact with one another. all fatigue studies were conducted through the use of an MTS 322 250 kN dynamic fatigue testing Process. The uniform cross section had a diameter in the center of 4 mm which led to a concentration of extremely localized stress. Using a CNC lathing machine, all specimens were made in accordance with DIN 50113. Vibration fatigue is a particular form of mechanical fatigue brought on by the vibration of machinery while it is in use. Similar to other types of fatigue, vibrations can start a crack path that could later spread and cause the equipment to collapse. An improved way is provided by vibration-fatigue methods, which calculate fatigue life based on Power spectral moments. In this manner, a value that would normally be determined using the time-domain method is guessed. It is not necessary to simulate time histories when dealing with several material nodes that exhibit diverse responses (such as a model in a FEM package). Then, it becomes feasible to compute fatigue life.at numerous sites on the structure using vibration-fatigue methods, and to accurately forecast where the failure will most likely occur. The constant frequency of beam is calculated by using frequency equation. The governing equations used in this analysis are given by:

$$w = 22.37\sqrt{\frac{EI}{ml^4}}$$

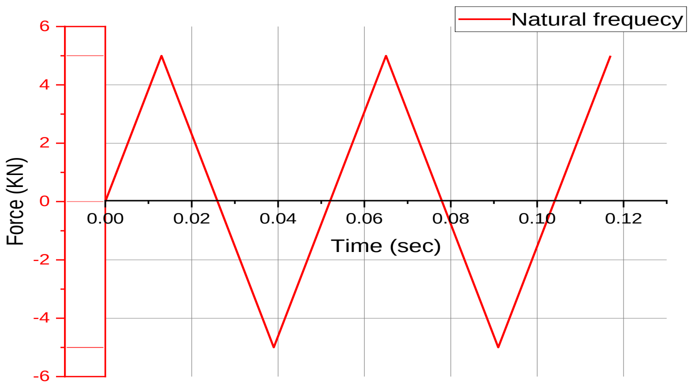

Figure 6. *Sinusoidal frequency of the pattern.*

The frequency-domain approach was used to examine the variables affecting the vibration fatigue life of an aluminum-nickel-Titanium specimen. In order to determine the inherent frequency and mode shape of each order, the model of the alloy beam was first created. The direction and natural frequency of the vibration that has the biggest influence on the structure was then determined using harmonic response analysis. Figure 6 The structure's fatigue life was then investigated. By altering the excitation load circumstances with the vibration value, the impact of the model method, natural frequency order, and frequency band variables on fatigue life was examined. The findings show that altering the power spectral density value can be used to perform the accelerated fatigue life test. The fatigue life is significantly influenced by the excite load during the first resonant frequencies. It is demonstrated that full frequency fatigue and central band fatigue have a quantifiable relationship. By calculating the specimen's fatigue life, influence variables for vibration fatigue behavior are examined via computation prototype of fatigue life, excitation load value, natural frequency order, and central frequency band range.

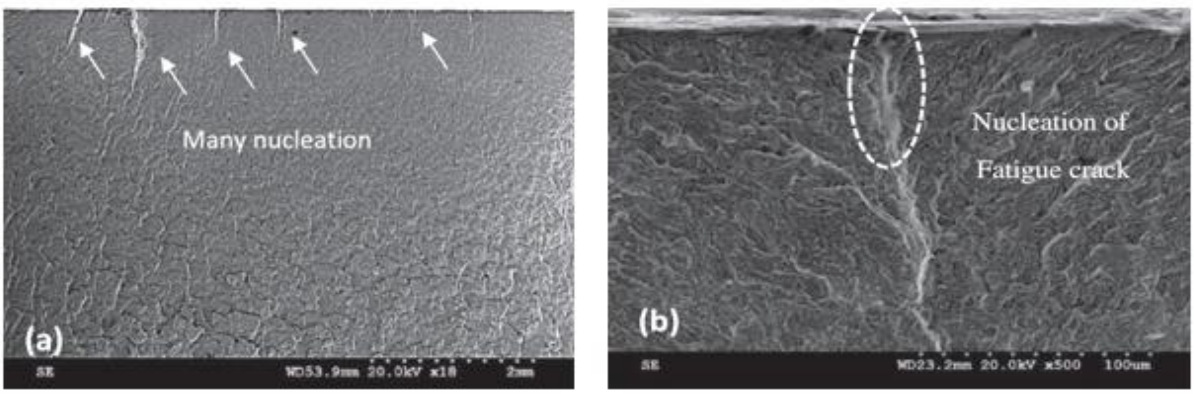

Figure 7: *Crack path micrographs.*

The fatigue fracture processes of the FGMs sample are shown in Figure 7. Regarding the latter, the level of applied stress had no bearing on the emergence of fatigue cracks at the specimens' surfaces. For example, stress concentrations occurred along the grooves or scratches left behind by surface machining. In fact, under low magnification, micro fractographic study of the fracture surfaces of carbonitrided sample revealed various modes of fracture.

The surface of the specimen contained all of the origins. They then connected into a single, deeper crack path. Striations from fatigue are also seen. With each loading cycle, the separation between the striations grew. Instead of being elliptic in shape, the major fracture is a single front of connected cracks that extends deeply into the specimen's substance.

4. Conclusion

Depending on the results obtained from the experimental testing the addition of titanium improves the mechanical properties of the Al-Ni alloy. The mechanical characteristics of the hybrid alloy improve as the titanium value and particle concentration increase. Compared to steel structural elements, they are more efficient, lighter, and less expensive. In contrast with the other layers, the wear rate of the first layer is highest during low load times and under low applied loads, with the fifth layer being the lowest value. However, as loads are used and load times increase, so does the wear rate of the fourth layer. The hybrid alloy exhibits good tensile test results and long-term fatigue stability when combined with Titanium. The entire fatigue life can be reasonably predicted using the fracture mechanic's approach. By utilizing random and continuous vibration, this method produces conservative estimations of fatigue lifetimes. Simplified analysis methods that assume a single fracture start site in the specimen thickness may produce additional errors by discounting the possibility of multiple crack edge. In comparison to the model used in this study, both of the later scenarios would lead to a shorter fatigue life.

References

1. Kim, E.-J., C.-M. Lee, and D.-H. Kim, *Study on the characteristics of functionally graded materials from Ni-20cr to Ti-6Al-4V via directed energy deposition.* Journal of Alloys and Compounds, 2023. **955**: p. 170263.
2. Aravind, R., K. Jayakumar, and R.K. Annabattula, *Probabilistic investigation into brittle fracture of functionally graded materials using phase-field method.* Engineering Fracture Mechanics, 2023. **288**: p. 109344.
3. Wang, Y., et al., *Microstructure and nanoindentation properties of high-throughput prepared Ti-Al2O3 functionally graded materials films.* Materials Letters, 2023. **337**: p. 133966.
4. Zheng, W., et al., *Effects of ceramic material in laser-directed energy deposition of titanium/ceramic functionally graded materials.* Journal of Materials Processing Technology, 2023. **317**: p. 117992.
5. Oza, M.J., et al., *Developing a hybrid Al–SiC-graphite functionally graded composite material for optimum composition and mechanical properties.* Materials Science and Engineering: A, 2021. **805**: p. 140625.
6. Parihar, R.S., S.G. Setti, and R.K. Sahu, *Recent advances in the manufacturing processes of functionally graded materials: a review.* Science and Engineering of Composite Materials, 2018. **25**(2): p. 309-336.
7. Korde, J.M. and B. Kandasubramanian, *Naturally biomimicked smart shape memory hydrogels for biomedical functions.* Chemical Engineering Journal, 2020. **379**: p. 122430.
8. Yongming, L., et al., *A novel functionally graded material in the Ti–Si–C system.* Materials Science and Engineering: A, 2003. **345**(1-2): p. 99-105.
9. Kratina, O., et al., *The Effect of polyglycols on the fatigue crack growth of silica-filled natural rubber.* Fatigue Crack Growth in Rubber Materials: Experiments and Modelling, 2021: p. 39-55.
10. Gent, A., P. Lindley, and A. Thomas, *Cut growth and fatigue of rubbers. I. The relationship between cut growth and fatigue.* Journal of Applied Polymer Science, 1964. **8**(1): p. 455-466.

11. Sukumar, N. and J.-H. Prévost, *Modeling quasi-static crack growth with the extended finite element method Part I: Computer implementation.* International journal of solids and structures, 2003. **40**(26): p. 7513-7537.
12. Lu, Y., Chen, Q., & Xiao, P., *Investigation of fatigue and fracture behaviors of functionally graded materials under random vibration loading.* Materials Science and Engineering: A, 2020. **780**: p. 138432.
13. Lu, H., Wang, C., Gong, Y., Song, S., & Ren, W., *Microstructural and mechanical properties of laser 3D printed AM60 magnesium–Aluminum functionally graded materials.* . Additive Manufacturing, 2020. **34**: p. 101360.
14. Ghasemi, M., & Rezvani, G. B. , *Study on the microstructure and mechanical properties of friction stir welded functionally graded nanocomposite.* 2019.
15. Daram, P., T. Hiroto, and M. Watanabe, *Microstructure and phase evolution of functionally graded multi-materials of Ni–Ti alloy fabricated by laser powder bed fusion process.* Journal of Materials Research and Technology, 2023. **23**: p. 5559-5572.