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Research Article

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Boundary Deformation Control for Flexible Heat Pipe Using NR-MWCNT based Joints

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Abstract

Being constrained by the onboard power source makes it more challenging to dissipate heat fast and dependably on satellite thermal control. Flexible heat pipes are proposed as a design solution to mitigate this problem. Designing and fabricating a suitable boundary topology to minimize the average stresses near the boundary in a heat pipe system of a spacecraft or satellite has been a prime research interest for industries and space organizations. The Heat pipe structure used in satellites and large spacecraft structures to dissipate heat is analogous to a cantilever beam supported at a hinge joint or fixed support. These joints of the cantilever beams in large structures are generally minimally damped due to the inadequate structural damping of the materials used and the lacking of other forms of damping, like air drag. In this research work, the flexible structure has been designed to increase the heat transfer rate and better resist stress concentration at the joint. The sinusoidal wavy surface is considered a conical frustum solid structure that connects the heat source and heat transfer pipe. One of the viscoelastic materials has been selected under the contemplation of the design solution. This paper aims to design a joint to reduce stress transfer from a heat pipe system to a host structure. And the joint should be conducted to transfer heat to the heat sink for dissipation.

Keywords

Flexible joint, Viscoelastic material, NR-MWCNTs

Introduction

Whenever any extended part of the system comes under static or dynamic load conditions, it always produces more stresses at the joint surface. Generally, in static condition, load comes due to its weight, and in dynamic due to acceleration and other external forces which causes moments. Due to the structural arrangement of the system, these produced stresses at the joint surface turn into stress concentration and result in failure. To avoid such failures, there is a need to develop or construct a flexible joint that reduces the stress concentration at the surface.

In this research work, the extended part is the heat transfer pipe, and the surface is the heat source. To resolve this problem, it is essential to ensure that the heat transfer rate maintains a specific value. The design of flexible structure joints has been published by researchers, which explains the relationship between surface structure and stresses and the variation of heat transfer rate [1-6]. The viscoelastic material has been used as a working material for a flexible joint which takes care of both flexibility and thermal conductivity. Researchers have presented their views on this aspect and its fabrication [7-13]. In light of the above

research article, this research aims to minimize the maximum stress concentration at the joint surface and maximize the heat transfer rate. The equation of the wave surface is given by:

$$y(x) = 0.5d + \left(\frac{l-x}{l}\right)\left\{\left(\frac{a-d}{2}\right) + b * \sin\left(\frac{2\pi x}{\lambda}\right)\right\} \quad (1)$$

Where, d is a smaller diameter, a is base diameter, l is total length, b is the amplitude of the sine wave, and a is the wavelength of the defined sine wave. The shape of the sinusoidal curve depends on the base diameter (a), the amplitude of the sine wave (λ), and wavelength (λ). It can be seen in figure 1. The objective is to maximize the heat transfer rate of the proposed flexible structural joint and to minimize the stress concentration at the source and the heat pipe joint. There are 3 design parameters a , b , and λ . By varying these design parameters, several joint geometries can be generated.

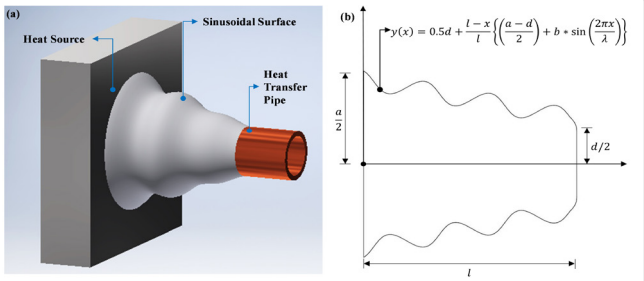


Figure 1: (a) Assembly of flexible joint with heat source and heat transfer pipe and **(b)** Geometrical description of the sinusoidal surface of a flexible joint.

There will be several possibilities that need to be optimized as per the design constraint. The stress concentration factors vary based on the curvatures present on the joint due to bending, axial, and torsion stresses. These stress concentration factors need to be minimized. The bending stresses and deflection have been compared with the proposed sinusoidal boundary of a flexible joint with an exponential boundary. Natural rubber and multi-wall carbon nanotube (NR-MWCNT) composite, viscoelastic material has been considered for the flexible joint. Rubber can improve stress concentration, and MWCNT can improve the thermal conductivity of joint material. An optimized combination of rubber and MWCNT has been considered, simultaneously improving the compliance modulus and thermal conductivity. The complex structure makes it challenging to correlate a flexible joint's geometry parameters and heat transfer capacity. A numerical simulation has been carried out to obtain a relation between design parameters and heat transfer capacity. The effect of the design parameter on temperatures has been analyzed with Analysis of variance (ANOVA) and obtained a regression equation. Further parameters have been optimized using the genetic algorithm optimization technique, and flexible joints have been fabricated.

Design Parameters of Flexible Joint

A comparative study has been carried out between sinusoidal [6] and exponential topologies.

$$y(x) = 0.5d + \left(\frac{l-x}{l}\right)\left\{\left(\frac{a-d}{2}\right)\exp\left(-\frac{x}{l}\right)\right\} \quad (2)$$

The general representation of a sinusoidal and exponential boundary is shown in Eq. 1 and Eq. 2, respectively. The comparisons of both topologies are based on Bending stresses and deflection for a given transverse load (F) [14].

$$\sigma = \left(\frac{32.M(x)}{\pi.d(x)^3}\right) \quad (3)$$

$$M(x) = F \text{ x } (l-x) \quad (4)$$

The top surface encounters the maximum bending stress, shown in Eq. 3. Bending moment at any 'x' (M(x)) is shown in Eq. 4. The deflection, $v(x)$, is found from the differential equation, shown in Eq. 5 [14], where 'E' is the young's modulus of the joint, and 'I' is the area moment of Inertia.

$$E \text{ x } I \text{ x } \left(\frac{d^2v}{dx^2}\right) = F \text{ x } (l-x) \quad (5)$$

Eq. 5 is complicated to solve as 'I' is a function of d(x) which is a complex expression of 'x'. Therefore, the Central difference finite difference numerical scheme is employed to find the deflection along x. The results are plotted for both Maximum bending stress and deflection condition and compared with both topologies. It can be observed that the sinusoidal boundary shows prominent results compared to the exponen-

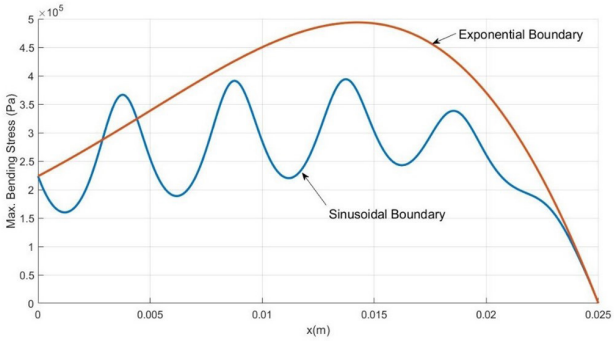


Figure 2: Bending stress due to transverse load along the x-axis.

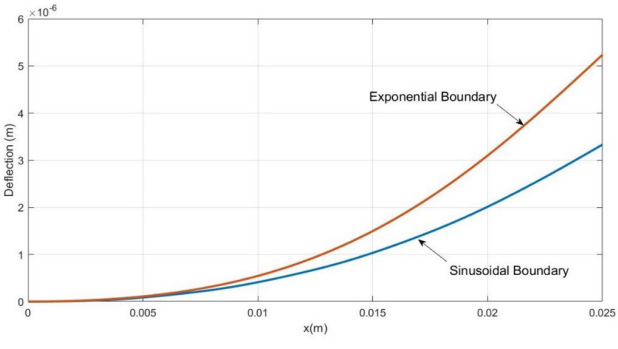


Figure 3: Deflection due to transverse load along the x-axis.

tial boundary shown in figure 2 and figure 3.

Simulation Results

The heat transfer phenomenon has been analyzed with a combination of different joint surface design parameters. Generally, deriving a direct relation between heat transfer capability and design parameters of the joint structure is challenging because of the complicated geometry. The boundary conditions are considered as uniform heat flux with a certain source and ambient temperature. The outer surface and joints are free from external loading. A numerical transient simulation has been conducted to compare heat transfer capability with specific design parameters. In this method, the thermal conductivity of the composite is considered a homogenous mixture. A combination of design parameters has been defined based on one of the designs of experiment techniques. The temperature of a specific point on the joint surface has been recorded and utilized to obtain a regression model with the ANOVA technique. To generate an empirical relationship between temperature and design parameters. In this method, we consider the thermal conductivity of the composite considering a homogenous mixture. In NR-MWCNT composite weight% of both materials dictate the mechanical and thermal properties of the composite. The thermal conductivity improves with an increase in the weight % of MWCNT and decreases the composite's compliance modulus. The optimum value of the weight% ratio has been obtained for these properties. A graphical representation of the weight % of MWCNT, compliance modulus, and thermal conductivity has been shown in figure 4.

The value of thermal conductivity corresponding to the optimum weight % of MWCNT has been used to perform eight numerical simulations in ANSYS. As explained earlier, it is also a problem of experiment design with 3 factors and 2 levels of configuration. The 2^3 design is a two-level factorial experiment design with three factors (say factors a, b, and λ). This design tests three main effects, a, b, and λ; three two-factor interaction effects, ab, $b\lambda$, and λa; and one three-factor interaction effect, $ab\lambda$. Analysis of variance technique has been considered for solving this problem. The calculation has been done using the MiniTab software tool to get the optimum solution and better regression model. The obtained regression equation is shown in Eq. 6.

Regression Equation in terms of temperature

$$t = 61.83 + 0.28a - 0.151b + 0.81\lambda - 0.02ab - 0.01a\lambda + 0.44b\lambda - 0.01ab\lambda \quad (6)$$

The temperature (t) at a considered point on the joint surface is a complicated function of a, b, and λ. The Axial, bending, and torsion stress concentration factors are functions of the radius of curvature (r), maximum diameter at that cross section (D), and depth of the groove (h) at any point on the surface. The standard formulation has been shown in Eq. 7 [14]. In the sinusoidal boundary case, the formulae for stress concentration factors and the D, r, h are given in Eq. 8, 9, and 10 [14, 15].

$$\text{Stress conc. Factor } (K_a/K_b/K_t) = C_1 + C_2\left(\frac{2h}{D}\right) + C_3\left(\frac{2h}{D}\right)^2 + C_4\left(\frac{2h}{D}\right)^3 \quad (7)$$

$$D(x) = 0.5d + \left(\frac{a-d}{2}\right) * \left(\frac{l-x}{l}\right) \quad (8)$$

$$r(x) = \frac{\lambda^2 l^2}{4\pi^2 b^2 (l-x)^2} \quad (9)$$

$$r(x) = \frac{\lambda^2 l^2}{4\pi^2 b^2 (l-x)^2} \quad (10)$$

The overall objective becomes simple here, to maximize the temperature (saturation temperature) and minimize the stress concentration factors using the formulae shown above. The objective function considered is of the form.

$$F_obj = \left(\frac{t^3}{K_a * K_b * K_t}\right) \quad (11)$$

The third power of t is considered only because three terms are to be minimized. So, to give equal importance to the numerator and denominator in the objective function, power 3 is considered. In the current problem, the population is a set of chromosomes whose genes are a, b, and λ. The best chromosome is observed by its objective function value, which is nothing but its fitness value. This best chromosome will have a better chance to survive for the next iteration (i.e., generation). Roulette wheel-based selection [15] is used to select the chromosomes for the next iteration. It is based on distributing the chromosomes with respect to their fitness values on a cumulative probability scale. The chromosome with maximum fitness value will have a bigger range in the cumulative probability scale than the other chromosomes and

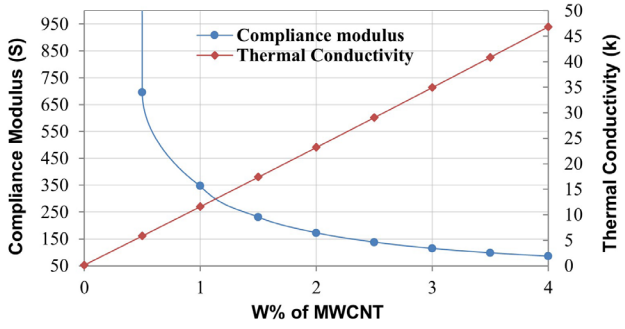


Figure 4: Compliance modulus and thermal conductivity plotted vs. weight % of MWCNT.

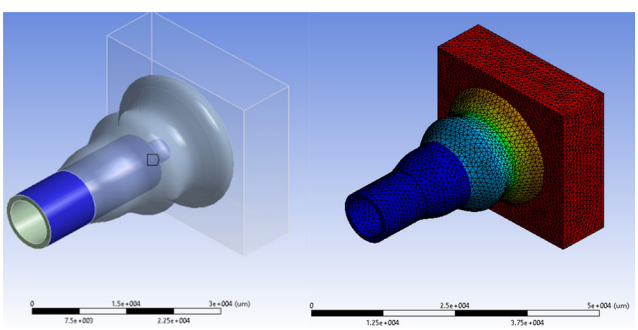


Figure 5: Assembly of parts and mesh views of Ansys simulation model.

thus have a better chance to select the next iteration based on generating a random number between 0 and 1. The Genetic algorithm is implemented in MATLAB with a population of 1000 and 500 iterations. The optimized result corresponds to a = 24.38 mm, b = 0.812 mm, and λ = 4.068 mm.

Fabrication of flexible joint

The NR latex is purchased from KA Pre-Vulcanized Latex Pvt. Ltd. (Chennai, India) and is pre-vulcanized. MWCNTs are obtained from Sigma-Aldrich. The surfactant for the dispersal of MWCNTs is sodium dodecyl sulfate (90%, Pragati Scientific Kanpur, India Poly (diallyl dimethylammonium chloride) (molecular weight 100,000 - 200,000, 20 wt. % in water) is purchased from Sigma-Aldrich. Several steps are involved in the fabrication of flexible joints. The basic standard process is shown in figure 6.After following all the steps, the fabricated flexible joints with many design parameter combinations are shown in figure 7.

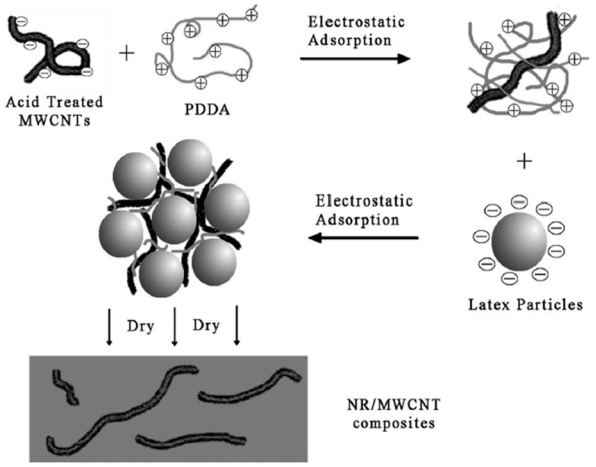


Figure 6: Schematic of the self-assembly process [8].

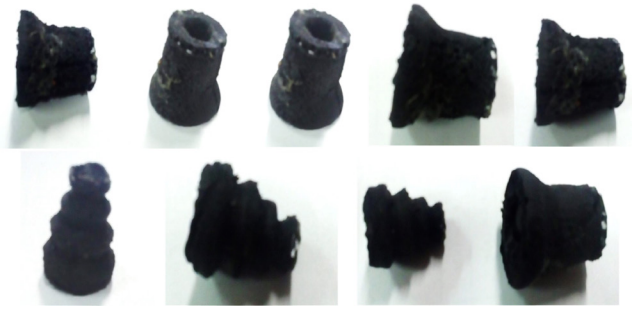


Figure 7: Fabricated flexible joints based on viscoelastic material.

Conclusion

In this work, a flexible joint with sinusoidal surface topology has been considered. It has been compared with exponential topology under a transverse load condition. The results show better performance in the case of sinusoidal topology. Further, a numerical simulation has been carried out to understand the proposed model's heat transfer capacity. A regression equation has been presented to establish a direct relationship between the design parameters and temperature at a certain point. The design parameters are further optimized with a genetic algorithm. The joint has been fabrication as per the standard procedure. A 10 x 10 mm^2 and a 2 mm thickness sample is tested on the laser flash test apparatus to validate the thermal conductivity. The thermal conductivity of the flexible joint is 15.1 W/(m-K), obtained experimentally and theoretically at 14 W/(m-K). This result can be considered with some error value. As results show, the designed sinusoidal surface topology is one of the methods to reduce the stress concentration factors. The mixture of NR and MWCNT with an optimized combination shows significant viscoelastic material properties. The proposed work can fulfill the specific purpose when compromising conditions with two properties exist, like thermal conductivity and compliance modulus. The experimental analysis with a fabricated flexible joint will be done in the future.

Table 1: Upper and lower limits of design parameters.

Factors/Levels	Low (-1)	High (+1)
a	22.5 mm	27.5 mm
b	0.5 mm	1.5 mm
λ	3	5

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Conflict of Interest

None.

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