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An Experimental Investigation of Fatigue Performance for A Flexure Spring

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Abstract: In order to prevent a free-piston Stirling cryocooler failure during mission life, the flexure spring's fatigue life is most critical and important. In the current research, an effort is made to examine fatigue life. The fatigue life testing of cryocooler flexures is frequently discussed in the literature. However, more information is needed about the economic approach and hardware needed for the testing. This research paper adopts the FEA approach of flexure spring and outlines the criteria for flexure fatigue testing. A moving coil linear motor was also designed and selected for the oscillating shaft and bending special-purpose flexure spring stack to validate stiffness criteria. The 10^8 no. of cycles required to validate the fatigue limit were also attained using the approach in a few days when testing at a relatively high frequency.

Keywords: Flexure springs, fatigue life, cry coolers, S-N curve

1. Introduction

Cryocoolers are devices that are used to produce extremely low temperatures, often in the range of -150 to -273 degrees Celsius. They are commonly used in space missions to cool sensitive equipment, such as infrared detectors and superconducting magnets. The significance of cryocoolers in space missions is that they allow for the operation of sensitive equipment at extremely low temperatures, which can be necessary for certain types of scientific experiments or technology. For example, infrared detectors are often used in space missions to study distant objects like galaxies and planets. These detectors require very low temperatures to operate effectively, so cryocoolers are used to cool them to the necessary temperature range.

In comparison to units using contact-type seals, the reliability and life of linearly driven cryocoolers have significantly increased because of wear-free, frictionless clearance seals. This has been accomplished by switching out the typical helical spring with an unconventional suspension system, known as flexural suspension or spring. In cryocoolers, the relevance of flexure springs is that they offer several significant advantages required for the essential performance of these devices. For instance, flexure springs are extremely small, lightweight, and compact, which is critical in miniaturized cryocoolers. In addition, they have a low thermal coefficient of expansion, owing to which they retain their flexibility over a broad range of temperatures, and they are highly flexible, allowing them to absorb shock

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and vibration. Flexure springs are a cost-effective option for cryocoolers and are preferred due to their ease of use and low-cost manufacturing. Flexure springs are used in cryocoolers specially to aid improve high reliability and performance designed for mission life. An exceptional kind of spring cum bearing - flexure spring bends a load moment to enable relative motion. A versatile metal disc with carved slots allows axial flexing while maintaining a higher radial stiffness. By bending the spiral arms, this spring maintains shafts that serve to perform a linear oscillating motion. A free-piston Stirling cryocooler houses a linear motor using flexure springs. As mentioned, fatigue life is the most critical parameter for cryocoolers considering around 10 years of mission life with reliable performance. Hence, failure is not acceptable considering mechanical properties viz. stiffness and ultimate tensile strength.

2. Special Purpose Flexure Spring

Figure 1 shows the actual geometry and features of a special-purpose flexure spring [1]. The special-purpose flexure spring cum bearing usually performs the following functions:

i. It maintains a free piston at a mean position with desired stiffness at high frequency.
ii. It enables free oscillation in the axial direction.
iii. It provides radial stiffness to prevent the free piston from contacting cylinder walls, thus maintaining tight clearance seals; and
iv. It helps with damping vibrations and prevents mechanical wear [2-4].

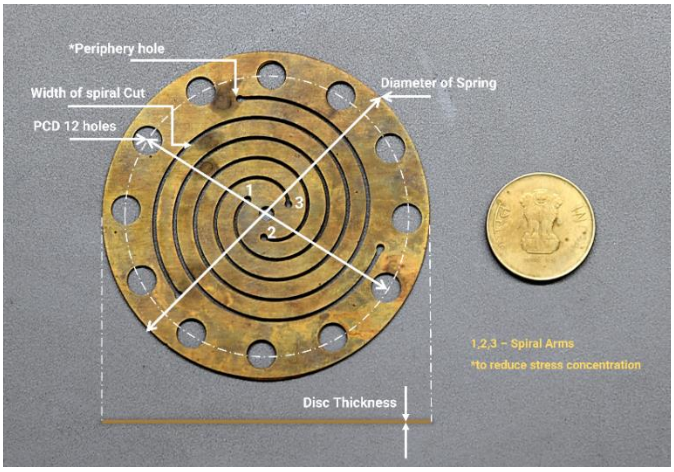

Fig. 1 - Actual geometry and features of a special-purpose flexure spring

Linear motors are utilized for greater performance and reliability in a standard cryocooler design. By axially bending the spiral arms, a specific purpose flexure spring enables relative motion. As a result of load deflection, the geometry features slots that permit axial motion. The spring aids in the oscillation of shafts in a linear motion. Linear motion is produced by the restoring force when a piston is coupled to a flexure spring. The flexure spring repeatedly displays elastic deformation because of the free piston's compression and expansion. The most notable characteristic of a flexure spring is that it functions as a spring being deformed in an axial direction (low stiffness value) and plays the role of bearing being distorted in a radial direction (larger stiffness value), respectively. The findings and literature are available for the design requirements, selection of material, experimental and theoretical analysis, and evaluation of fatigue of these flexure springs [1-3], but limited data is in the research domain regarding the specifics of testing procedures and fatigue life validation.

Figure 1 depicts an exceptional metal disc of the flexure spring that is the subject of the experimental investigation. Each flexure spring is provided with three spiral grooves that provide three distinct spiral arms that support the radial and axial loads during operation. A 560^{o} angle is traversed by each spiral arm. The disc is tightly clamped to a support structure using twelve holes. The holes are significantly large in the bolt size to provide for ease of radial alignment and to take into consideration any misalignment between the relevant mating components. A close fit for the shaft is made possible by the disc's central hole. Additionally, to help with stress relief and concentration periphery holes are provided where spiral grooves end and the same was validated using the FEA approach. An analysis using the Finite Element method was performed on a specific type of flexure spring to determine the effects of key parameters on achieving an infinite fatigue life during the operation of a cryocooler without failure. The FEA methodology is used in the current research project along with the ANSYS software. The geometrical features configuration of a particular flexure spring was determined through a parametric analysis.

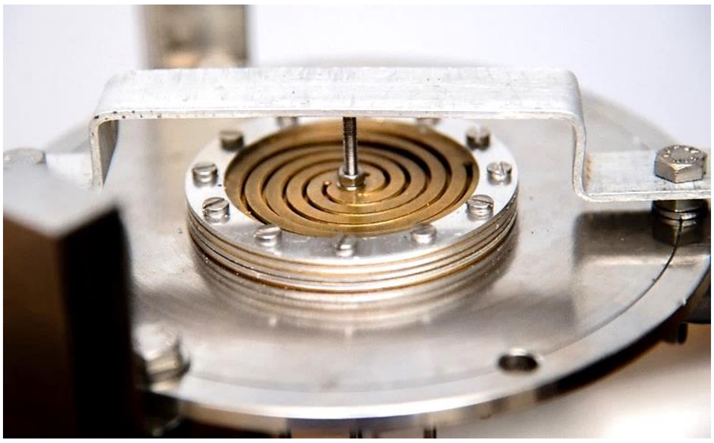

Fig. 2 - A stack of flexure springs assembled with spacers

Figure 2 illustrates a setup compressor unit's assembly employing flexure springs assembled for the experimental investigation with the limiting stroke mechanism. To achieve the appropriate axial and radial stiffnesses, enough flexure discs are parallel stacked, one on top of the other. For dynamic stability, two of these stacks are utilized. The flexure bearing has a far higher radial stiffness than the helical spring, which buckles easily. The flexures deflect by 5 mm provided with the stroke limiter at the central position during actual linear compressor operation since the piston rod's 5 mm stroke operates at a 50 Hz frequency.

3. Design Requirements and Material Properties

When materials are exposed to changing loads and strains, known as fluctuations, fatigue gets developed. After a significant number of fluctuations, fatigue may lead to cracks or fractures. Cyclic stress, tensile stress, and plastic strain all act together in unison to generate fatigue fractures. Fatigue cracking won't start and spread if any one of these three conditions is missing. Generally, a crack gets initiated due to cyclic stress, while the tensile stress causes the crack to spread (crack propagation). A compression load may result in fatigue even while compressive stress won't. There are three stages in the fatigue process:

i. Initial wear-and-tear damage that causes crack start and nucleation.
ii. Crack propagation is the process of a crack gradually growing in size until the remaining, uncracked cross-section of a part becomes too weak to withstand the stresses being applied (crack propagation).
iii. The remaining cross-section finally fractured suddenly.

Typically, cyclic loads that are much lower than the material's static yield strength cause fatigue cracking. Any specimen's or structure's fatigue life is determined by how many stress (strain) cycles must occur before failure. This value depends on a wide range of factors, including the material's metallurgical state, the stress level, the stress state, the cyclic waveform, and the fatigue environment. Regarding the design specifications for a specialized flexure spring, three crucial parameters were taken into account: axial stiffness, radial stiffness, and fatigue strength.

i. Axial Stiffness: The flexure spring should resonate with the moving mass on the combined action of the gas spring above the piston and the flexure bearing below it to reduce the power required by the linear motor of the compressor. The axial stiffness of the flexure bearing is typically kept lower than the stiffness of the gas spring above the piston to control the degree of vibrations in the unit.
ii. Radial Stiffness: The flexure bearing assembly must have sufficient radial stiffness to maintain the clearance seal under the combined weight of the piston-shaft sub-assembly, coil, and coil support.
iii. Fatigue strength: Alternating strains are applied to each arm of a flexure disc at a rate similar to the linear motor's operating frequency. The maximum stress in a disc depends on the spiral profile, diameter, and thickness of the disc for a given axial movement. This maximum stress value should be significantly below the material's endurance limit to ensure that the disc has virtually infinite life.

The Finite Element Analysis (FEA) method was used to determine various physical and geometrical characteristics, such as load stresses, displacement, width of cut, stress concentration zone, number of spiral arms, spiral traverse angle, thickness of metal disc, etc. And for the experimental investigation of the special-purpose flexure spring, a testing setup for validation of fatigue life was constructed and made to justify the findings. Since the evaluation was run for 10^8 cycles, the findings were supported. In order to proceed ahead for material selection, impact on spring properties viz. modulus of elasticity, yield strength, tensile strength, hardness, elastic limit, spring deflection limit, and fatigue strength were considered for investigation [5]. Based on the FEA iterations and results, materials viz. Grade 5 Titanium (Ti-6Al-4V-3.7165-R56400), AISI SS 302, AISI SS 304, Beryllium Copper 17000, Beryllium Copper 17200 (TH), and AMPCOLOY® 944 were chosen for a flexure spring considering the material and mechanical properties.

Figure 3 illustrates stress and stiffness variations of the flexure spring with deformation values for AISI SS302, AISI SS304, Beryllium Copper 17000, Beryllium Copper 17200 TH, Grade 5 Titanium, and AMPCOLOY 944. According to the results and investigation findings, Ti-6Al-4V exposes higher deformation and lower stress values, whereas AISI SS 304 reveals lower deformation and higher stress values. When compared to the other five material selections while retaining the same boundary conditions, Beryllium Copper 17200 TH yields the optimal deformation and stress values.

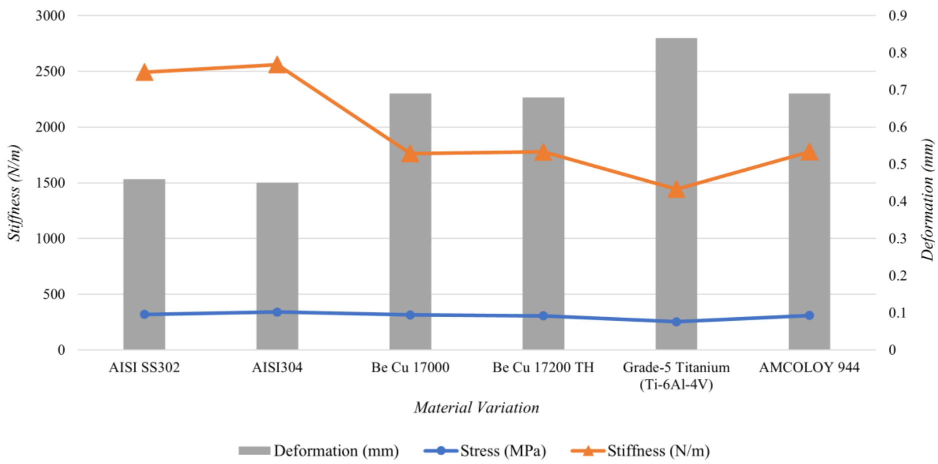

Fig. 3 - Stress and stiffness variations of special-purpose flexure spring for AISI SS302, AISI SS304, Be Cu 17000, Be Cu 17200, Grade 5 Titanium and AMPCOLOY 944

4. Fatigue Life Testing

Fatigue life testing for flexure springs is crucial because it allows for determining the number of cycles that the spring can endure before failure. Flexure springs are often subjected to repeated loads, and it is critical to know their fatigue life to ensure the assembly's safety and reliability. Fatigue testing is typically done by clamping the flexure springs at both ends and applying a cyclic load, which is controlled and monitored using a linear motor. An experimental configuration for testing setup for fatigue life was created in order to confirm the flexure spring's special function. The actual working Fatigue Life Test Setup is displayed in Figure 4. The configuration was put up so that mounting the motor unit and the flexure mounting plate was convenient and easy. The set-up for the testing fatigue life includes legs, a base plate, a mounting plate, a reciprocating shaft, a coil former, a magnet, a yoke, a pole piece, an inner spacer, an outer space, a fastener, a dead weight, etc. The legs, base plate, mounting plate, reciprocating shaft, and spacers are made of AISI SS 302; the central bush is made of brass; most of the parts of the test setup are made of non-magnetic materials. A copper wire is twisted onto the Delrin material of the coil former, which serves as the linear motor. The top pole piece is made of soft iron, which is affixed to the neodymium magnet (Nd-Fe-B) and then enclosed in a casing, making up the linear motor's static component. Pure iron, which has a powerful magnetic field and a high permeability, is used to make the casing and pole piece. The soft iron's saturation flux density, which is on the order of 2.1 Tesla, is high enough to satisfy the current need. The legs, mounting plate, and base plate are produced using the milling process.

5. Design of Custom Linear Motor

In order to compress gas in the compressor at the optimum motor efficiency, a linear motor must be designed to produce the necessary power output. A moving coil linear motor uses the principles of electromagnetism to generate motion in a linear direction, rather than the circular motion of a conventional electric motor. It works by using a stationary magnet and a coil of wire that is attached to a moving component, such as a slider or a carriage. A magnetic field is generated by the coil when an electric current is delivered through it, and this field interacts with the field of the stationary magnet. This interaction causes the coil to move along the direction of the magnetic field, generating linear motion. The speed and direction of the motion can be controlled by adjusting the strength and polarity of the electric current.

The efficiency of the motor is also restricted by limitations on the magnet's size and overall weight. The magnetic flux that is accessible in the gap is influenced by the magnet material. A coil for the linear moving coil motor is positioned in the magnetic gap. In the gap, the coil oscillates back and forth when an AC supply is provided. The compressor piston and displacer, which reciprocate, are connected to corresponding motor coils.

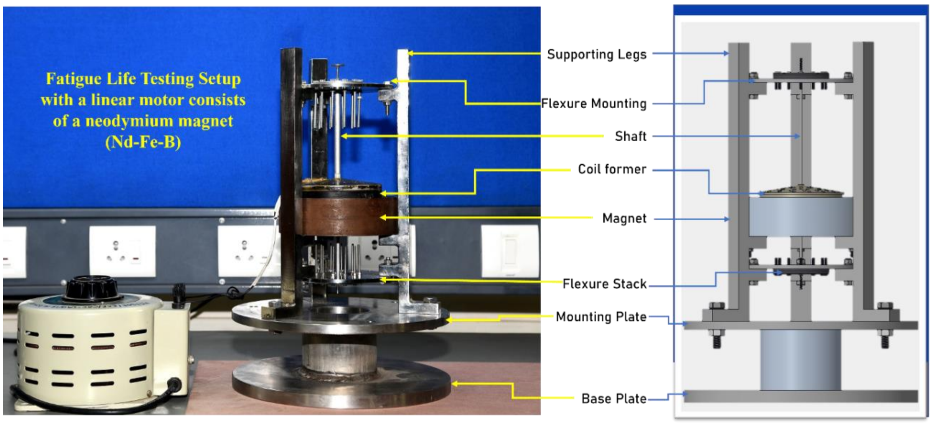

Fig. 4 - Actual fatigue life testing setup with a custom linear motor having neodymium magnet

The design of a linear motor with moving coils mainly included: (1) Design of the magnetic circuit: The magnet and pole parts must be sized to create one or two working gaps that are the right height and width, while also limiting flux loss by eliminating flux leakage through channels other than the working gaps. Single magnetic gap motors are taken into consideration in this research work and (2) Coil design: The width and height of the coil are determined by the quantity of layers and turns in each layer that make up the windings, respectively. The height and width of the magnetic gap must be fixed in line with this requirement in order to maintain the required separation between the coil and the inner surfaces of the pole piece. The following criteria were taken into account when designing a linear motor

a) The magnetic gap must first be created with the necessary flux density.
b) The inductance, resistance, height, and active length of the wire are critical coil parameters.
c) Voltages, current, supply frequency, and the phase difference between the supply voltage and piston movement.
d) The piston's movement's amplitude, the height-to-coil ratio, and the height of the magnetic gap.

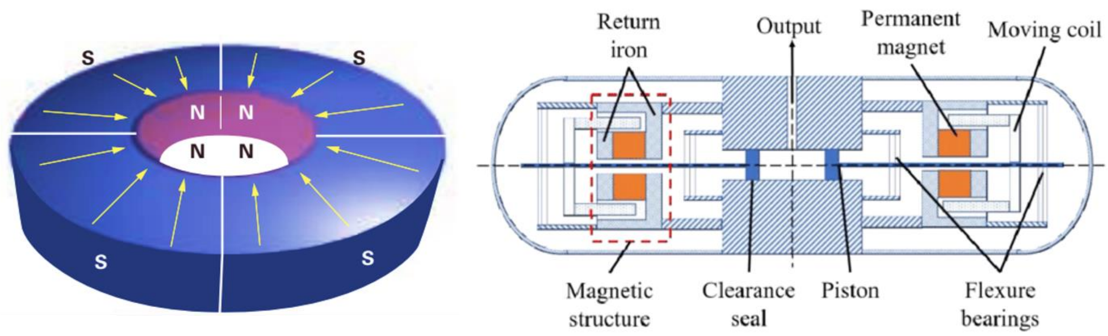

Fig. 5 - Schematic of moving coil used in linear motor

The diagram of a linear motor with a moving coil, which was used as the drive mechanism in the research, is illustrated in Figure 5. Higher speed and acceleration, more accuracy, and the absence of backlash are all notable advantages that linear motors have over these well-established methods. The usage of NdFeB permanent magnets benefits direct-drive linear motors. To increase a magnet's magnetic characteristics in a specific direction, anisotropy is added to it. Anisotropy can be radial, axial/transverse, or both, for instance, in a ring magnet. A lot of the time, fabricating radially orientated rings is the most cost-effective option. These rings cost much less than sintered NdFeB rings and are widely used in rotating DC motors.

Table 1 represents design specifications obtained for the moving coil linear motor used for the free-piston Stirling machine. In order to perform experimental testing, flexure springs require a significant displacement of ± 5 to 25 mm stroke with relatively low forces, but traditional fatigue testing requires a tiny displacement and larger forces. Hence ordinary industrial fatigue test equipment is typically not adequate. When testing springs with commercial equipment, it is possible to utilise dynamic amplification to test the springs at resonance so that a slight movement of the test device causes a significant spring movement.

In the test setup that was customized from the earlier research, experiments were carried out [5]. The linear compressor comprises a specific-purpose flexure spring for suspension, a linear motor, and a piston-cylinder assembly. A maximum motor efficiency of 73% was recorded when the manufactured linear motor was tested. The motor was put through testing with no load. The experiment aimed to ascertain the motor's resonance frequency when it was not under load. By doing this, measuring the variance in power, power factor, and current at different frequencies at a fixed stroke length of roughly 5 mm was possible. This research paper examined a unique moving coil linear motor for a free piston Stirling device.

Table 1 - Moving coil linear motor design specifications

Sr. No.	Design Parameters	Values
1	Operating frequency (Hz)	50
2	Power output of motor (W)	30
3	Magnet material	Nd-Fe-B
4	Pole piece material	Soft iron
5	Saturation flux density (T)	2.1
6	MMF loss factor	1.45
7	Magnet flux density (T)	0.8285
8	Gap flux density (T)	0.545
9	Coil height (mm)	20
10	Diameter of the copper wire (mm)	0.45
11	Total resistance of coil (Ohm)	16.45
12	Efficiency of the motor (%)	73

6. Results and Observations

Theoretically, the special-purpose flexure spring has an infinite fatigue life when taken into account along with the structural characteristics of the spring, such as shape, size, spiral arm, and thickness, as well as the properties of the beryllium copper material. Using ANSYS FEA, chosen spring and stress conditions are applied, resulting in flexure with an infinite fatigue life. Later, the fatigue life test setup was run for 10^8 cycles on stacks of special-purpose flexure springs, and no cracks or failures were observed during that number of cycles, validating the infinite life of the springs. Using the setup for a fatigue life test, the analytical results were further confirmed and validated. Even high pressures and cyclic stress can be tolerated by the material Beryllium Copper 17200 (TH). The maximum stress that can be exerted over a predetermined number of cycles without leading to a fracture is known as fatigue strength. A LOG-LOG S-N curve showing the stress range vs the number of cycles to failure is produced by taking data from physical fatigue testing and using linear regression. S-N curves can be used to estimate how many load cycles a material will withstand before failing. The curves are used to identify the fatigue stress conditions that lead to fracture initiation, growth, and eventual total failure. The S-N curve for various selected materials was plotted and is shown in Figure 6, where it is possible to see how the maximum and minimum stress relate to cyclic failure. With the help of the accompanying figure, it was determined that the performance of the fatigue life is significantly affected by service stress and surface condition.

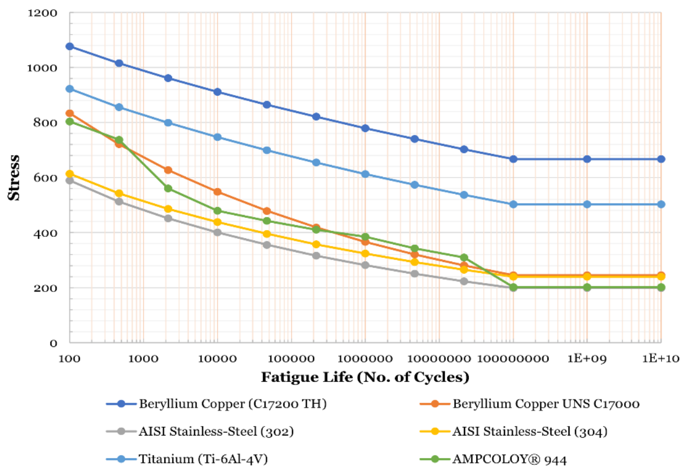

Fig. 6 - S-N Curve plotted for AISI SS302, AISI SS304, Be Cu 17000, Be Cu 17200 TH, Grade 5 Titanium, and AMPCOLOY 944

The present research aims to improve the performance and extend the service life of a flexure spring by increasing its stiffness and reducing operating stresses through optimal settings. Beryllium Copper 17200 (TH) was found to have excellent static strength, toughness, and work hardening capacity, making it suitable for distributing strain and resisting fatigue failure. The fatigue crisis must be considered when choosing materials and designing flexure springs, as they are subject to continual cyclic loads, which will increase reliability. The predicted fatigue life using the S-N curve was confirmed through testing by using the experimental number of cycles before failure. Acceptable values of 10^8 cycles were obtained for a flexure spring made of Beryllium Copper 17200 (TH) using FEA. This material is stiffer than titanium and AMPCOLOY 944 and has superior fatigue strength than steel. Flexure springs used in linear compressors require maximum displacement, minimal stress, and enhanced stiffness.

7. Conclusion

The fatigue life testing setup and moving coil linear motor manufacturing and design have been completed. The magnetic flux densities of the ring magnets were measured. The specially designed flexure springs, which were parametrically tuned and optimized, show high radial stiffness and low axial stiffness values, which make them suitable for the current research study. Experimental measurements were made to determine the production and restoring forces. The magnet assembly's restoring force was measured for a ± 5 mm displacement and was found to be greater than the force needed to achieve the design goal. A no-load test was conducted on the motor's entire assembly. Experimental research was done on a motor with a constant stroke length of about 5 mm to find the resonance frequency. The fatigue life test setup was successfully run for 10^8 cycles with stacks of special-purpose flexure springs in order to validate infinite life, and no cracks or failure was observed during the no. of cycles.

Acknowledgement

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