Very High–cycle Fatigue Testing of Space Instrument Materials

Osman Macit
Dr Jicheng Gong
Department of Engineering - Faculty of Natural, Mathematical & Engineering Sciences

Project Background

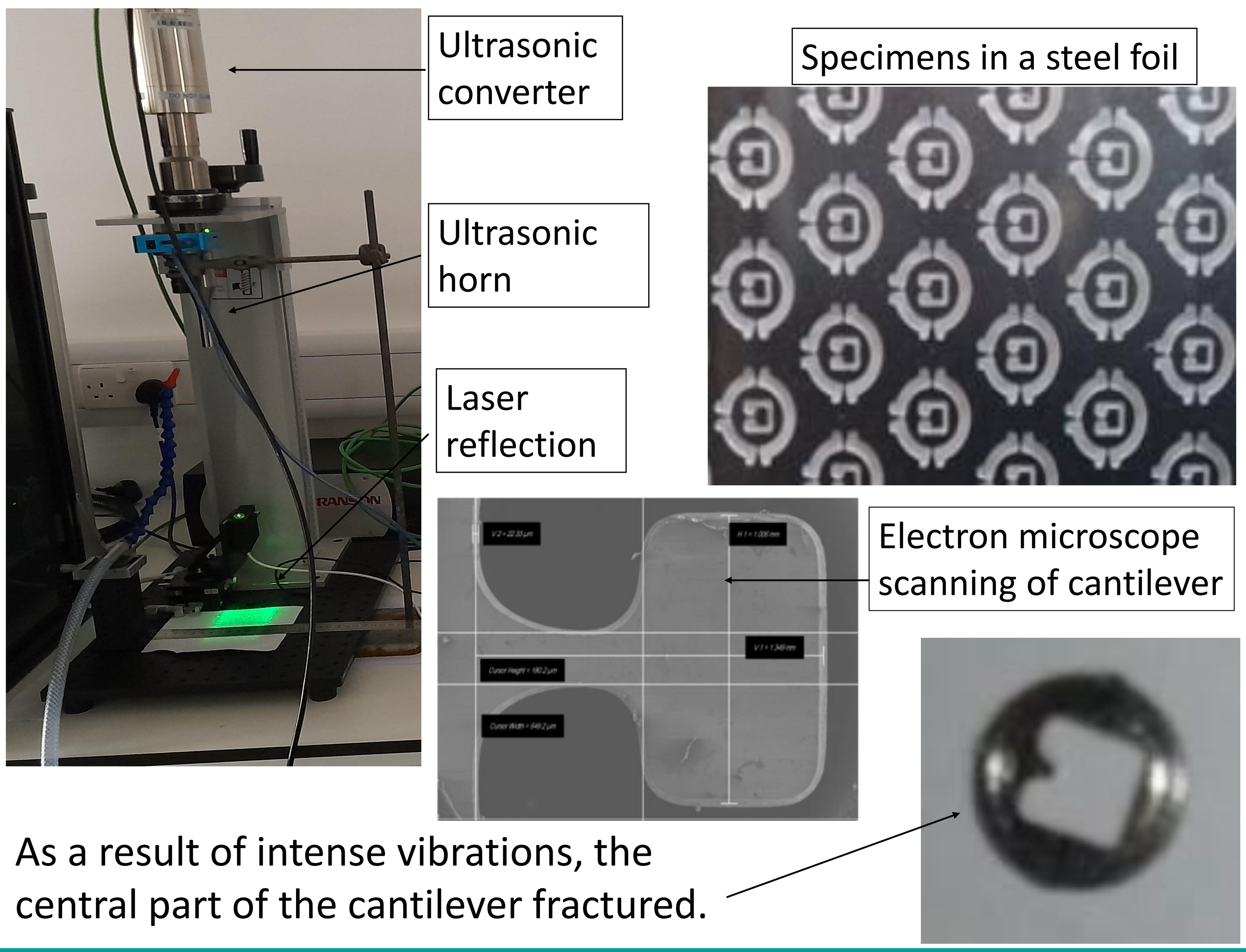
Space missions often require instruments that function reliably for decades. Many of their components are subject to very high–cycle fatigue (VHCF) loads. For example, space coolers, such as a Joule-Thomson (JT) Cooler which are used to maintain the temperature of sensitive detectors, need to last for at least 10^{10} cycles [1]. However, little is known in this regime, and without robust VHCF data, designers and manufactures of space coolers face uncertainty in predicting the lifespan and reliability of their components. One critical challenge in VHCF tests is the assessment time, which can take years or even decades to collect one set of data [2]. To overcome this issue, we have developed a novel small–scale ultrasonic fatigue testing method, enabling the simulation and analysis of stress distribution.

Introduction

This project aims to apply the ultrasonic fatigue testing method to evaluate the VHCF behaviour of 304 stainless steel – a material widely used in space coolers. Through detailed stress analysis and modelling, the experiment seeks to identify crucial stress points and can provide valuable data that will help predict and improve the longevity of aerospace components, especially within VHCF conditions.

Experiment

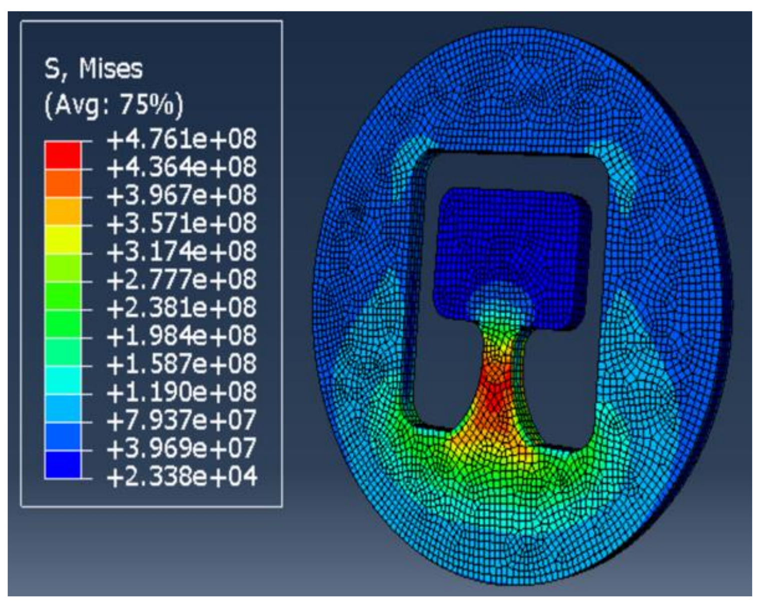
The experiment involved using an ultrasonic fatigue cantilever, which was placed beneath a CR-20C converter, a component that converts electrical energy into ultrasonic vibrations. The converter induces high frequency vibrations into the cantilever, and by pointing a laser upwards towards the cantilever, we were able to measure its deflections.



As a result of intense vibrations, the central part of the cantilever fractured.

Modelling

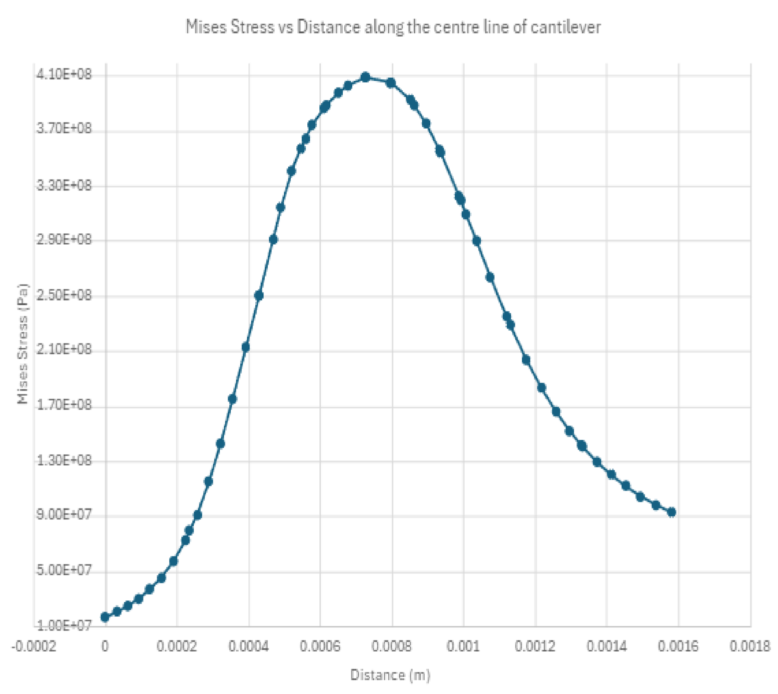
This process and the effects of the vibrations can be modelled in Abaqus. As the model shows, the central part of the cantilever is where the material faces the most stress, reaching a peak stress of 409 MPa. This is because the transition point between the outer circular section and the middle rectangular section is small in length, causing the vibrations to spread less and focus on that point, ultimately causing it to reach its failure point and break off.



Results and discussion

The tangent of the deflection angle can be calculated, and this is measured to be 0.0302. A low tangent value indicates that the cantilever is more rigid and resistant to bending under cyclic loads, which would imply a stiffer material. As the cycle testing increases, the tangent of the deflection angle increases due to fatigue damages, and the angle can help predict how the material will behave over time with respect to the evolution of fatigue crack initiation and crack growth in stainless steel. For engineers and designers, they would want a high tangential angle (correspond to greater fatigue strength) for high cycle testing, because this would mean the material would be better suited for high intensity outer space conditions. The stress per unit angle can also be calculated, and this is measured to be 13500 MPa. The high value indicates that small angular deflections result in significant stress, suggesting that the meso-cantilever specimen is highly sensitive to deformation.

The graph of Mises stress vs Distance along the centre line of the cantilever can be plotted. The graph shows how quickly the stress increases, and then decreases in value, further amplifying how much stress the small curved section experiences compared to the rest of the cantilever.



Conclusion

The results of this study have important implications for the design and longevity of space instruments. Understanding the stress distribution and deflection behaviour after going through very high–cycle fatigue tests allows for more accurate predictions of material failure, enabling the design of components that can reliably withstand the extreme conditions encountered in space.

References

[1] Crook, M. (2020) Cooler Developments at STFC: 2K-30K coolers in support of space science missions [PDF]. presentation. https://www.ralspace.stfc.ac.uk/Pages/ASC2020_Martin%20Crook_%20JT%20Cooler%20Developments%20at%20STFC%20-%202K-30K%20coolers%20in%20support%20of%20space.pdf.
[2] Jacquemain, V. et al. (2021) 'Estimation of stress in specimens loaded with ultrasonic fatigue machines,' International Journal of Fatigue, 153, p. 106474. https://doi.org/10.1016/j.ijfatigue.2021.106474.