Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 45 (2010) 460–467

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Shock protection of penetrator-based instrumentation via a sublimation approach

T. Hopf*, S. Kumar, W.J. Karl, W.T. Pike

Optical and Semiconductor Devices Group, Department of Electrical and Electronic Engineering, Imperial College, London SW7 2BT, UK

Received 10 September 2008; received in revised form 13 August 2009; accepted 13 August 2009

Abstract

It is often necessary for space-borne instrumentation to cope with substantial levels of shock acceleration both in the initial launch phase, as well as during entry, descent and landing in the case of planetary exploration. Current plans for a new generation of penetrator-based space missions will subject the associated on-board instrumentation to far greater levels of shock, and ways must therefore be found to either ruggedize or else protect any sensitive components during the impact phase. In this paper, we present an innovative method of shock protection that is suited for use in a number of planetary environments, based upon the temporary encapsulation of said components within a waxy solid which may then be sublimated to return the instrument back to its normal operation. We have tested this method experimentally using micromachined silicon suspensions under applied shock loads of up to 15,000*g*, and found that these were able to survive without incurring damage. Furthermore, quality factor measurements undertaken on these suspensions indicate that their mechanical performance remains unaffected by the encapsulation and subsequent sublimation process.

Keywords: Microelectromechanical systems and devices; Shock and shock reduction and absorption; Seismology; Space-borne and space research instruments; Apparatus and components

1. Penetrator missions

The combined use of fly-bys, orbiting spacecraft and landers for space exploration have over the last few decades revolutionized our understanding of the planetary bodies in our solar system. All of these approaches, however, have been primarily geared towards the extraction of scientific information about a planet's surface. There remains important data about the interior of these bodies which can only be obtained via physical emplacement of probes in sub-surface locations (for example, seismological (Lognonné, 2005) and heat flow (Hagermann, 2005) measurements). This fact has led to proposals for penetrator-based missions (Simmons, 1977) which would impact a probe into the planetary body at high speed, embedding it and its associated instrumentation several metres below the surface.

Instrumented penetrators have a long pedigree in military applications, but in context of their use in planetary missions the technology is still very much in its infancy. Penetrators were included on the Mars-96 (Surkov and Kremnev, 1998) and Deep Space 2 (Smrekar et al., 1999) missions, but their failure, along with the cancellation of the more recent Japanese LUNAR-A mission (Mizutani et al., 2003) has meant that as yet no penetrator has been successfully deployed off Earth. Nevertheless, there are at present a number of missions both proposed and ongoing that will be penetrator-based (Collinson, 2008): these include current lunar missions (UK's MoonLITE (Gao et al., 2008) and Russia's Luna-Glob (Galimov, 2005)), as well as proposed future missions to Jupiter's moon Europa (Mitri, 2002) and to Saturn's moons Titan and Enceladus (Coustenis, 2008).

---

* Corresponding author. Tel.: +44 0 2075 946 242; fax: +44 0 2075 946 308.

E-mail address: tobyhopf@gmail.com (T. Hopf).

0273-1177/$36.00 © 2009 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2009.08.015

Aside from the scientific advantages that come from sub-surface placement, penetrators also offer an inexpensive and simpler alternative when compared to traditional lander missions, especially since they dispense with the need for a complex entry, descent and landing phase. This often means that several penetrators can be included on a single mission, providing redundancy in case of failure as well as allowing data to be obtained from several different locations on a planet. The high mass associated with soft landers also tends to make their utilization impractical on certain planetary bodies like Europa or Enceladus (Collinson, 2008), which leaves a penetrator-based approach as an attractive option; particularly since their sub-surface location helps to shield them from the harsh radiation environments of these worlds. On the other hand, the use of penetrators comes with its own disadvantages: mission timescales will generally be short due to the lack of any long-term power supply, and all instrumentation and its electronics must be ruggedized so that they are capable of withstanding the very high shock levels associated with impact.

2. Shock protection

One good example of the need for effective shock protection mechanisms for penetrator-based instrumentation is the microseismometers (Pike et al., 2006) which are proposed for the UK's MoonLITE mission. These are three-axis short-period seismic sensors and will be utilized to measure the size and physical state of the lunar core, as well as studying crust and mantle structure and moonquake events (Gao et al., 2008). The basis of the seismometer design proposed for MoonLITE is a micromachined silicon suspension that is fabricated by Deep Reactive Ion Etching (DRIE) through a 0.5 mm thick wafer (Fig. 1a) with lateral dimensions of 20 mm × 20 mm. This suspension consists of a large proof mass which is connected to an outer frame via a series of springs, with a resonant frequency of around 10 Hz. Intermediate frames are also built into the design in order to minimize off-axis motion and reduce the vertical sag of the suspended proof mass (Pike and Kumar, 2007).

The microseismometer itself consists of this silicon suspension enclosed by a pair of glass capping dies (Fig. 1b), with the movement of the proof mass due to a seismic event detected via electrodes patterned both on the silicon suspension and the upper glass die. Lateral motion of the proof mass leads to a change in electrode overlap, which can then be measured as a change in capacitance. Spiral coils are fabricated onto the edge of the proof mass to allow for magnetic actuation, and thus to provide feedback control of the system. Permanent magnets placed either side of the silicon suspension form a magnetic circuit, and a current applied to the coils will then cause displacement of the proof mass due to the Lorentz force. All electrical inputs and outputs are routed from external electrodes, which are connected to the proof mass via thin metal traces running along the silicon springs.

Single-crystal silicon was chosen as the fabricating material for these suspensions primarily due to its excellent mechanical properties (Peterson, 1982), which allow for the miniaturization of the design (Pike et al., 2004). The disadvantage of this selection is that silicon is a brittle material, and is thus easily susceptible to shock-induced breakages. The suspensions had previously undergone random vibration testing on a dynamic shaker table, and were found to be able to sustain a maximum of 75*g* in-plane and 35*g* out-of-plane acceleration before damage began to occur. This damage manifested itself as fractures at the linkages of the springs (the weakest part of the suspension), as well as in surface spallation. The penetrators that will be used in MoonLITE, on the other hand, are expected to impact at a speed of around 300 m/s, causing a peak shock deceleration on the order of 10,000*g*; enough to bury them 2–5 m under the lunar surface. Naturally, the much higher levels of shock that are associated with a penetrator impact will require substantial modification to the existing seismometer design, either by ruggedizing the suspension itself or else by providing some external protection mechanism against the shock.

To achieve the former is difficult since any substantial changes to the suspension in this regard will invariably act to adversely affect the sensitivity of the seismometer,

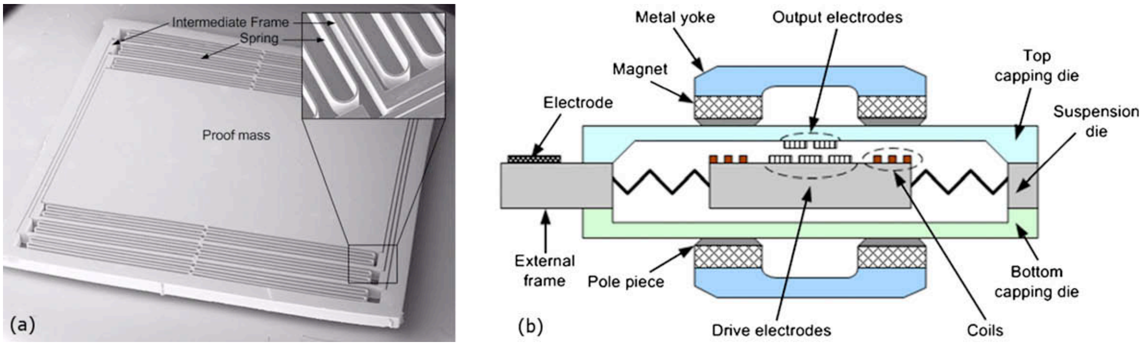

Fig. 1. (a) Micromachined silicon suspension for use in a microseismometer. (b) Schematic of the packaged microseismometer, showing the silicon suspension sandwiched between two glass capping dies.

which leaves an external protection mechanism for the suspension as the preferred option. There are a number of potential methods of shock protection which have been previously utilized in shielding similar MEMS technologies, and which could be perhaps also be considered for use in this case. For example, mechanical latching (Syms et al., 2004), electrostatic clamping (Hartley, 1999) and electromagnetic clamping (Ikuta et al., 1992) of the central proof mass are all potential possibilities. One problem with utilizing electrostatic or electromagnetic clamping, however, is that both methods would require an external power source to sustain the clamping mechanism throughout the entire high-shock impact phase. Moreover, electromagnetic clamping would not at any rate represent a realistic approach for these devices, since calculations show that supplying sufficient current through the coils to be able to resist a 10,000*g* shock acceleration is simply unfeasible.

Another key concern with all of the approaches mentioned above is that they remain unsuitable mechanisms for either clamping or damping the spring elements of the suspension. These springs are thin silicon flextures, and can undergo large motion even at relatively low accelerations. When they come into collision either with the frames or the proof mass they will often sustain physical damage, in certain cases enough to fracture the suspension. One way to circumvent this problem would be to utilize an encapsulating material in order to fully restrain these components. Microelectronic devices and circuits are often permanently embedded in resins for survival in high-shock environments like space applications (Harper, 1964). This technique is obviously inappropriate for the protection of a seismometer, however, or indeed of any other mechanical device which requires freely moving parts for its operation. An alternative approach is to embed the structures to be protected in a material which is able to be removed subsequent to the high-shock loading in order to return the device back to its original working condition.

To achieve this requires a material which is strong enough to provide such protection while solid, yet easily disposed of after it has achieved this purpose, either by melting and subsequent evaporation or else directly by sublimation. A material which can be removed via sublimation is the preferred option, since this will not interfere with any of the electronic components present on the devices and is less likely to leave behind unwanted residue. The release of this material could then be mediated by a seal that would act to contain the sublimant both during launch and transit to the Moon, but which would nevertheless be weak enough to be broken during the high shock phase associated with penetrator impact, allowing sublimation to commence.

The use of such sublimating materials has previously been proposed for space applications, both for use in shock protection (O'Sullivan and Pezdirtz, 1964) as well as in the timed release of components (for example, time-delayed biphenyl plugs for releasing chamber doors in space (Wilken et al., 1997)). The reason that such an approach has particular appeal in this case is largely due to the nature of the MoonLITE mission. The use of penetrators, rather than landers, to deliver a scientific payload to the lunar surface will require the instrumentation to be far more shock-hardened than in other missions. In addition, the lack of any atmosphere on the Moon will provide a near-perfect vacuum, potentially allowing for the extremely rapid and clean sublimation of any encapsulated instruments which are exposed to such an environment, even at temperatures below 0 °C.

3. Sublimation theory

The choice of an appropriate encapsulating material to suit this purpose requires an understanding of the parameters that will govern the sublimation process. The sublimation rate of a solid material is generally a complex function of its vapour pressure, the external pressure to which it is exposed, and the airflow of the surrounding environment (Tesconi et al., 1997). The situation becomes greatly simplified, however, when the material exists in an extremely low-pressure environment such as the Moon, since the effects due to these latter two factors will now become negligible. When this is the case, the sublimation rate will be maximized, since by lowering the external pressure that the material is exposed to it becomes possible to reduce the temperature that will be needed for rapid sublimation (Fig. 2). In such a circumstance, the sublimation rate will then be given by the Hertz–Knudsen equation (Sherwood and Johannes, 1962):

$$\dot{m} = \alpha P_s \sqrt{\frac{M}{2\pi R T_s}} \tag{1}$$

where $\dot{m}$ is the mass flux in g/cm^2 s, α is the evaporation coefficient of the material in question, P_s is its surface vapour pressure (in mm Hg), M is its molecular weight, R is the gas constant, and T_s is the surface temperature of the material (in K). Thus, in order to maximize the rate

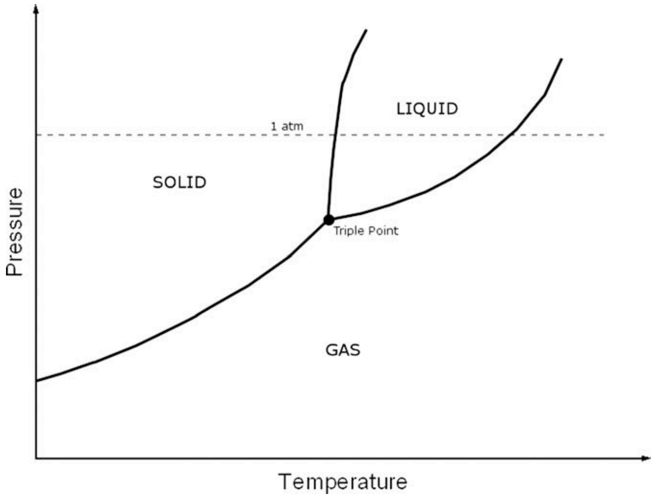

Fig. 2. Typical phase diagram for a material. A reduction of the external pressure will allow for a direct transition of the material to the gas phase via sublimation.

of mass loss one requires a substance which will display a high vapour pressure even at moderate temperatures.

There exists a wide array of sublimable materials that fit this criterion. These do not belong to any particular chemical class, but are instead determined empirically based on vapour pressure measurements. The temperature-dependence of the vapour pressure of a solid material can generally be given by the well-known Antoine equation (DeDoes et al., 2007):

$$\log P_s = B - \frac{A}{C + T_s} \tag{2}$$

where A, B and C are empirically derived constants known as the Antoine coefficients, and are characteristic of the particular material (Yaws, 1994). Aside from a high vapour pressure, there are also other important qualities that any encapsulating material should display in order to render it suitable as a protective mechanism for high-shock applications. Firstly, it must have a melting point that is significantly higher than room temperature at Standard Temperature and Pressure (STP), to ensure that it will remain solid for as long as the protection is required. In addition, it should also be non-toxic, to make the handling and encapsulation processes as easy as possible, as well as to ensure that there is no danger to individuals should the seal on the material be accidentally broken.

To investigate the feasibility of using such materials for encapsulation, three different chemicals that fulfilled the above-mentioned criteria were chosen to conduct experimental studies of shock protection on the seismometer suspensions previously discussed. The chemicals that were selected on this basis were naphthalene, paradichlorobenzene (PDB), and camphor. Naphthalene is perhaps the most commonly utilized sublimating chemical for scientific purposes, since its sublimation behaviour serves as the basis for a common method of mass and heat transfer measurement (Goldstein and Cho, 1995). PDB is also a well-known sublimant, and finds its major application in industry as the principle ingredient utilized in most mothballs and urinal cakes. Finally, camphor is another widely used chemical: its non-toxicity at low doses has meant that it is often utilized in cooking, and this along with its sublimation behaviour has also led to a number of proposals for its employment as a method of drug delivery (Aly et al., 2005; Koizumi et al., 1997).

The successful utilization of a sublimation approach towards shock protection will require not only the survival of the sensitive mechanical elements, but also the subsequent sublimation of the protective material both cleanly and within a reasonable time period. This latter concern can be addressed by looking at the predictions that arise from theory. The parameters of the sub-surface lunar environment are fairly well-constrained, due to the experimental efforts that were undertaken during the Apollo missions (Langseth et al., 1972). From these, it can be ascertained that at a depth of around 1 m below the surface, the seismometers would be exposed to a sub-surface temperature of approximately 250 K, with this value varying negligibly with time, due to the poor thermal conductivity of the regolith.

Knowing this, the period of time that would be required for each of the three chosen chemicals to completely sublime may then be estimated using Eq. (1). Complete encapsulation of the seismometer suspensions would require a total sublimant volume of around 0.4 cm^3, and by assuming that a leak area of 1 mm^2 could be provided to mediate the escape of the material to the surrounding vacuum via sublimation, approximate sublimation times can be calculated. The results of this calculation are shown in Table 1, both at the expected lunar sub-surface temperature, as well as at room temperature for comparison. The numbers that are obtained from this clearly demonstrate that even at 250 K both PDB and camphor will be able to completely sublime within a timeframe that should be acceptable even for a mission with a short lifetime. Naphthalene, on the other hand, has a much longer sublimation time at low temperature. This does not necessarily preclude its use in this context, however, since in theory the sublimation process could be greatly accelerated by providing some heating to the seismometer, via the application of a current through its feedback coils.

As previously mentioned, the Moon is an excellent candidate for a sublimation approach, since it combines a negligible atmospheric pressure with a relatively moderate sub-surface temperature. What will the general applicability of this technique be, though, in terms of penetrator-based missions to other planetary bodies? In many cases, we believe that it would remain a viable approach for a number of other potential targets for penetrator missions, even though conditions would be not quite as benign. For example, both Europa (Hall et al., 1995) and Enceladus (Dougherty et al., 2006) share the negligible atmospheric pressure that is so advantageous for sublimation, yet both also have much lower temperatures, which will tend to make the process far slower. In such cases, external heating of the devices would most likely be required in order to achieve complete sublimation within a reasonable time period. On the other hand, targets like Titan (Harri et al., 2006) – which retains a significant atmosphere and has a pressure similar to that of Earth – would obviously be much less appropriate for a shock protection method based on sublimation.

4. Experimental results

In order to fully encapsulate the structures that were to undergo shock testing, a small metallic container was

Table 1
Calculated sublimation times of different sublimating materials for MoonLITE seismometers exposed to lunar vacuum.

Sublimating material	Sublimation time at 250 K (days)	Sublimation time at 300 K (days)
Camphor	13.9	0.6
Naphthalene	172.5	1.7
Paradichlorobenzene	0.5	0.02

placed onto a hotplate and the solid sublimants then added until they had melted and completely filled the interior. It was then taken off the hotplate and left to cool and solidify. When this process was complete, the suspensions were placed on top of the solid layer that had been formed and the container then placed back on top of the hotplate. The re-melting of the sublimant now caused the suspensions to sink slowly down into the container, ensuring full encapsulation of all its elements. The hotplate was then turned off and the sublimant was left to slowly cool and re-solidify.

In order to ensure rapid sublimation, the suspensions that had undergone encapsulation were subsequently placed into a vacuum chamber at room temperature, which was then evacuated to a vacuum level of $\sim 10^{-3}$ torr. After this had been done, a visual inspection of the suspensions was undertaken to see whether any damage had occurred, followed by more detailed inspection of the structures using a scanning electron microscope (SEM). Apart from evaluating its usefulness as a shock protection mechanism, the main concerns associated with this process were whether it would allow for the complete and clean removal of the sublimating solid in order to return the suspension back to its original condition, as well as the effects of any potential stresses that might be applied to the suspension structures during the solidification phase (Lei et al., 2002).

4.1. Solidification stress

Solidification stress is generally the result of adhesion of the coating substance to the surfaces of the structure being coated; this acts to limit in-plane shrinkage during the solidification process, and has previously been shown to be large enough to cause deformation or even breakages of components that have been coated (Kim and Kim, 1997). To evaluate the effects that would be associated with the stress induced by the solidification process, a large number of suspensions were first encapsulated and then released by sublimation to ensure that no damage would result from this. All of the suspensions were carefully inspected prior to encapsulation to verify that they were free from damage. In total, 15 suspensions were encapsulated in PDB, 15 in naphthalene, and 5 in camphor.

Of these, the suspensions that were encapsulated in camphor fared by far the worst. SEM imaging performed on suspensions released from camphor showed multiple breakages occurring at the spring linkage points – the weakest part of the structure – for all five suspensions that were tested (see Fig. 3). Inspection of the naphthalene-encapsulated structures revealed better results, with 10 of the 15 suspensions surviving without any damage, while the other 5 still suffered from breakages occurring in the spring linkage region. The findings from the PDB-encapsulated suspensions were much better, with 14 out of 15 surviving intact, while a single suspension manifested one broken spring, again occurring at a linkage point.

These results are most likely related to the melting points of the three sublimants, with the speed of the subsequent cooldown and solidification process being greatly affected by this. Camphor has a melting point of 179.75 °C at STP, and thus undergoes a rapid solidification when the hotplate is switched off. Naphthalene has a melting point of 81.2 °C at STP, and so experiences a somewhat gentler phase transition. PDB, with a melting point of only 53 °C at STP, takes the longest time to cool and solidify, which should act to reduce the stresses experienced in the springs. The resistance of these suspensions to stress-related breakage is therefore likely to be able to be increased substantially merely by introducing a slower and more controlled cooldown phase, although further experimental studies on this question are still required.

4.2. Quality factor measurements

To assess whether there would be any effect on the mechanical performance of the seismometer suspensions due to the solidification and subsequent sublimation of the chosen encapsulating material, tests were carried out to measure the quality factor, *Q*, of these suspensions both before and after the encapsulation process. In mechanical systems, the quality factor is a dimensionless parameter which indicates the rate at which the system dissipates its energy. This figure therefore gives an indication of the mechanical performance of a structure, and is of crucial importance in seismometer fabrication, since the mechanical noise of a suspension can be shown to be inversely pro-

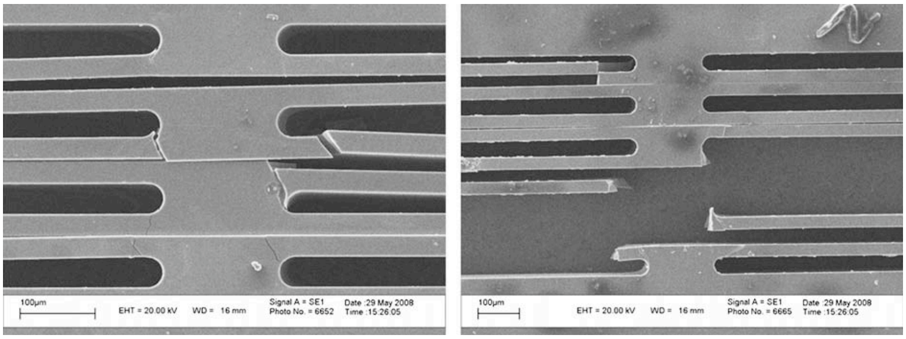

Fig. 3. SEM images of solidification stress-induced breakages of the suspension springs when utilizing camphor as the sublimating material.

portional to the square root of its quality factor (Usher, 1973).

The quality factor of a suspension can be measured by utilizing an SEM as a vibrometer (Pike and Standley, 2005). A large vibration is induced in the suspension (by tapping on the SEM), and the exponential ringdown of this vibration is then plotted. From the time period of this decay the quality factor of the suspension can then be easily extracted. By operating the SEM in variable-pressure mode, a range of measurements at different chamber pressures can be performed (Fig. 4). These measurements were taken using a LEO VP 1400 SEM operating at 20 kV, which is capable of imaging samples in variable-pressure mode for pressure values between 1 and 400 Pa.

The inability of camphor to undergo the solidification process without unacceptable damage to the suspensions resulting, meant that only PDB and naphthalene remained viable candidates for encapsulation. After initial measurements of the suspension's quality factor in the SEM, the encapsulation and sublimation processes were carried out, with the suspension then put back into the SEM chamber to re-measure the quality factor. The results obtained from these measurements, taken at a range of different chamber pressures, are displayed in Fig. 5. Variation of quality factor with pressure is expected if rarefied gas damping dominates, whereas the sublimant residue contribution would be expected to be independent of the pressure (Pike and Standley, 2005). As can be seen, the effects of the encapsulation process on the quality factor of the suspension appear to be negligible, with differences between individual measurements all falling within the margin of error of the measurement technique being utilized, and the expected variation of damping with gas pressure dominating the behaviour. This confirms that, at least in the case of PDB and naphthalene, it is possible to achieve a clean sublimation of the encapsulating material without any residual effect on the performance of the suspension that has been coated.

4.3. Shock testing

Having ascertained that the process of encapsulation could be carried out without permanent damage being done to the suspension, the crucial test was now to establish whether it could actually provide the protection that would be required under high shock loads. To determine this, two penetrator impact trials were conducted by the UK MoonLITE consortium at the QinetiQ facility in Pendine, Wales, with a sand target used in order to simulate the lunar regolith. The impact velocity of the projectile was ~310 m/s, with an impact angle ranging from 88° to 108°. The projectile's angle of attack and presence of a flare at the end created a 'tail slap' resulting in high vertical shock acceleration.

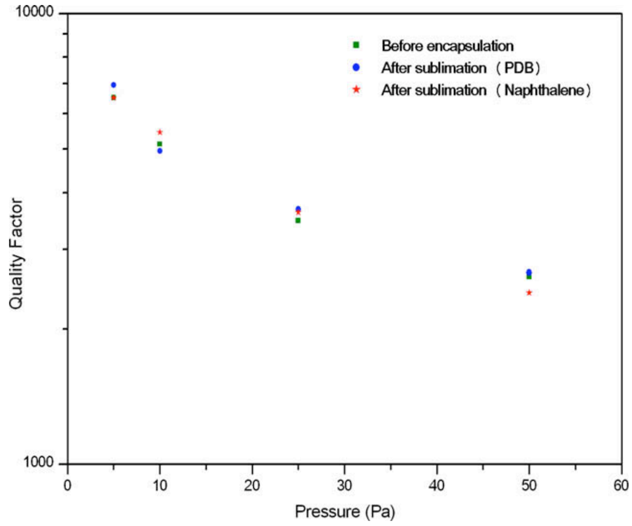

Fig. 5. Plot of quality factor values before and after sublimation, based on SEM ringdown measurements taken at various chamber pressures.

Fig. 6 shows the shock acceleration profile along the three axes before, during and after the penetrator hits the target. The measured on-axis peak acceleration was 20,000*g* at the front of the penetrator and around 10,000*g* at the rear of the penetrator (Fig. 6a). The lateral peak accelerations were measured at the rear of the penetrator and were 15,000*g* along the vertical axes (Fig. 6b) and 6500*g* along the horizontal axes (Fig. 6c). The compartment containing the suspensions was located approximately in the middle of the penetrator and so would have been exposed to similar or higher levels of shock loading.

In both of the trials, the penetrator contained five suspensions encapsulated in PDB and another five that were encapsulated in naphthalene. These were all housed inside filled metal containers with a lid screwed on to seal in the sublimants, and the containers themselves were bolted

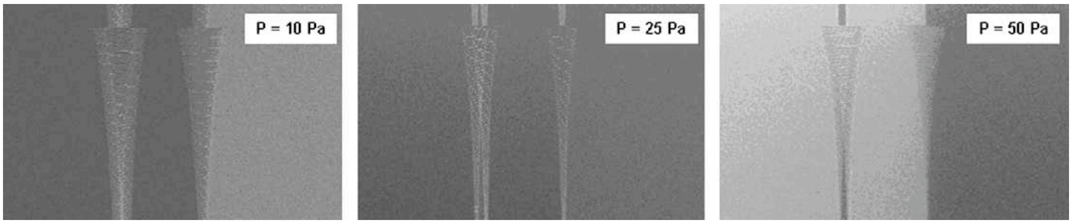

Fig. 4. SEM vibrometry measurements of the ringdown of silicon springs as a function of the chamber pressure. The timescale is the same for all plots. An exponential decay of the vibration envelope is observed in each case, and this may then be used to determine the quality factor of the suspension at a given pressure.

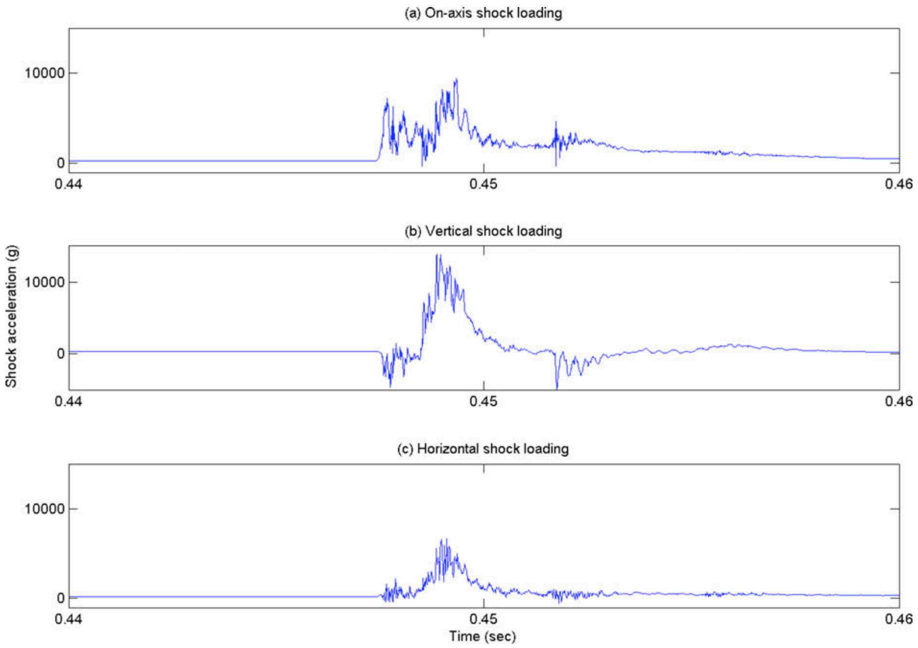

Fig. 6. Shock acceleration profiles taken from the rear of a penetrator impacting a sand target at ~310 m/s: (a) on-axis shock profile; (b) vertical-axis shock profile; (c) horizontal-axis shock profile.

onto the interior wall of the penetrator. Visual inspection of the encapsulated containers after impact showed that the sublimants were all still solid and intact, and had not suffered any cracking or damage. Sublimation of the encapsulants was then carried out under vacuum, and a detailed inspection of the suspensions was performed. In all cases, it was found that for both trials the suspensions had survived the shock intact, and that their springs displayed no visible signs of damage or distortion. These results lead us to conclude that a sublimation approach to shock protection can indeed provide a viable approach for ensuring the survival of sensitive components during penetrator-based impacts.

5. Conclusion

A method of shock protection based on the temporary encapsulation of instrumentation within a solid but sublimable material was proposed, primarily geared towards utilization on penetrator-based space missions. This approach was first examined theoretically, and determined to be feasible for the case of planetary bodies which manifest a very thin or negligible atmosphere. Experimental studies were then carried out which showed that the encapsulation and subsequent sublimation of components could be achieved without either causing damage to them or otherwise adversely affecting their mechanical performance, with PDB in this respect being the most promising of the three sublimants tested. Finally, it was demonstrated using penetrator impact tests that this technique could be used to successfully protect sensitive components against shock levels of up to 15,000*g*, by utilizing either naphthalene or PDB as the encapsulating medium.

Acknowledgments

This work has been funded by the Science Technology and Facilities Council. The authors would like to acknowledge Professor Manuel Grande for pointing out the existing use of sublimants in space technology, Prof. Alan Smith, Dr. Rob Gowen and QinetiQ for organizing the penetrometer trials, Craig Theobold for providing mechanical fabrication support, and Kerrin Rees for providing the accelerometer data.

References

Aly, A.M., Semreen, M., Qato, M.K. Superdisintegrants for solid dispersion: to produce rapidly disintegrating Tenoxicam tablets via camphor sublimation. Pharm. Technol. 29, 68–79, 2005.

Collinson, G. The UK Penetrator Consortium. Planetary penetrators: the vanguard for the future exploration of the solar system. J. Br. Interplanet. Soc. 61, 198–202, 2008.

Coustenis, A. The TandEM Consortium. TandEM: a mission for Titan and Enceladus in situ exploration within ESA's Cosmic Vision. Geophysical Research Abstracts 10, EGU2008-A-11894, 2008.

DeDoes, A.J., Goetz, M.D., Misovich, M.J. A simple approach to vapour pressure prediction. Chem. Eng. Prog. 103, 39–44, 2007.

Dougherty, M.K., Khurana, K.K., Neubauer, F.M., Russell, C.T., Saur, J., Leisner, J.S., Burton, M.E. Identification of a dynamic atmosphere at Enceladus with the Cassini magnetometer. Science 311, 1406–1409, 2006.

Galimov, E.M. Luna-Glob project in the context of past and present lunar exploration in Russia. J. Earth Syst. Sci. 114, 801–806, 2005.

Gao, Y., Phipps, A., Taylor, M., Clemmet, J., Parker, D., Crawford, I.A., Ball, A.J., Wilson, L., Curiel, A., Davies, P., Sweeting, M., Baker, A. Lunar science with affordable small spacecraft technologies: MoonLITE & Moonraker. Planet. Space Sci. 56, 368–377, 2008.

Goldstein, R.J., Cho, H.H.A. Review of mass transfer measurements using naphthalene sublimation. Exp. Therm. Fluid Sci. 10, 416–424, 1995.

Hagermann, A. Planetary heat flow measurements. Philos. Trans. Roy. Soc. A 363, 2777–2791, 2005.

Hall, D.T., Strobel, D.F., Feldman, P.D., McGrath, M.A., Weaver, H.A. Detection of an oxygen atmosphere on Jupiter's moon Europa. Nature 373, 677–679, 1995.

Harri, A.-M., Mäkinen, T., Lehto, A., Kahanpää, H., Siili, T. Vertical pressure profile on Titan – observations of the PPI/HASI instrument. Planet. Space Sci. 54, 1117–1123, 2006.

Harper, C.A. Resins for embedding microelectronic devices. IEEE Trans. Compon. Packag. Technol. 11, 22–27, 1964.

Hartley, F.T. Micro pump technology and applications, in: Proceedings of the SPIE Conference on Electronics and Structures for MEMS, Qld., Australia, pp. 403–409, 1999.

Ikuta, K., Aritomi, S., Kabashima, T. Tiny silent cybernetic actuator driven by piezoelectric device with electromagnetic clamp, in: Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems, Travemünde, Germany, pp. 232–237, 1992.

Kim, J.Y., Kim, C.J. Comparative study of various release methods for polysilicon surface micromachining, in: Proceedings of the IEEE Micro Electro Mechanical System Workshop, Nagoya, Japan, pp. 442–447, 1997.

Koizumi, K., Watanabe, Y., Morita, K., Utoguchi, N., Matsumoto, M. New method of preparing high-porosity rapidly saliva soluble compressed tablets using mannitol with camphor, a subliming material. Int. J. Pharm. 152, 127–131, 1997.

Langseth Jr., M.G., Clark Jr., S.P., Chute Jr., J.L., Keihm, S.J., Wechsler, A.E. The Apollo 15 lunar heat-flow measurement. The Moon 4, 390–410, 1972.

Lei, H., Francis, L.F., Gerberich, W.W., Scriven, L.E. Stress development in drying coatings after solidification. AIChE J. 48, 437–451, 2002.

Lognonné, P. Planetary seismology. Annu. Rev. Earth Planet. Sci. 33, 571–604, 2005.

Mitri, G. Preliminary design for a Europa mission, in: Proceedings of the 33rd Annual Lunar and Planetary Science Conference, Houston, TX, 2002.

Mizutani, H., Fujimura, A., Tanaka, S., Shiraishi, H. T. LUNAR-A mission: goals and status. Adv. Space Res. 31, 2315–2321, 2003.

O'Sullivan Jr., W.J., Pezdirtz, G.F. Method and apparatus for shock protection. U.S. Patent 3,160,950, 1964.

Peterson, K.E. Silicon as a mechanical material. Proc. IEEE 70, 420–457, 1982.

Pike, W.T., Standley, I.M., Trnkoczy, A. Micro-machined accelerometer. U.S. Patent 6,776,042, 2004.

Pike, W.T., Standley, I.M. Determination of the dynamics of micromachined lateral suspensions in the scanning electron microscope. J. Micromech. Microeng. 15, S82–S88, 2005.

Pike, W.T., Standley, I.M., Syms, R.R.A. Micromachined suspension plate with integral proof mass for use in a seismometer or other device. U.S. Patent 7,036,374, 2006.

Pike, W.T., Kumar, S. Improved design of micromachined lateral suspensions using intermediate frames. J. Micromech. Microeng. 17, 1680–1694, 2007.

Sherwood, T.K., Johannes, C. The maximum rate of sublimation of solids. AIChE J. 8, 590–593, 1962.

Simmons, G.J. Surface penetrators – a promising new type of planetary lander. J. Br. Interplanet. Soc. 30, 243–256, 1977.

Smrekar, S., Catling, D., Lorenz, R., Magalhaes, J., Moersch, J., Morgan, P., Murray, B., Presley, M., Yen, A., Zent, A., Blaney, D. Deep space 2: The Mars microprobe mission. J. Geophys. Res. 104, 27013–27030, 1999.

Surkov, Y.A., Kremnev, R.S. Mars-96 mission: Mars exploration with the use of penetrators. Planet. Space Sci. 46, 1689–1696, 1998.

Syms, R.R.A., Zou, H., Yao, J., Uttamchandani, D., Stagg, J. Scalable electrothermal MEMS actuator for optical fibre alignment. J. Micromech. Microeng. 14, 1633–1639, 2004.

Tesconi, M., Pikal, M.J., Yalkowsky, S.H.A. Method for the rapid estimation of sublimation rates of organic compounds at standard temperature and pressure. J. Pharm. Sci. 86, 1299–1302, 1997.

Usher, M.J. Developments in seismometry. J. Phys. E: Sci. Instrum. 6, 501–507, 1973.

Wilken, B., Axford, W.I., Daglis, I., et al. RAPID – the imaging energetic particle spectrometer on Cluster. Space Sci. Rev. 79, 399–473, 1997.

Yaws, C.L. Yaws' Handbook of Vapor Pressure: Antoine Coefficients. Gulf Publishing Company, TX, USA, 1994.