Journal of Materials Science & Surface Engineering Vol. 3 (1), 2015, pp 190-194

Contents lists available at http://www.jmsse.org/

Journal of Materials Science & Surface Engineering

# Enhancing the Fatigue Life of an Electronic Package in Spacecraft

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Article history

Received: 01-May-2015
Revised: 25-May-2015
Available online: 01 July, 2015

**Keywords:**

Electronic Package,
Beryllium-Aluminium,
AM162,
Fatigue Life

## Abstract

The structural components of spacecraft and its sub systems should be made-up of materials, which should resist distortion, withstand dynamic environment, that occur during the launch and on-orbit conditions. The spacecraft launch environment is quite harsh which can damage its electronics. The high stresses that occur during this phase are transmitted to the spacecraft structures and its electronic equipment which affect its fatigue life. The electronic packages in the spacecraft plays vital role in carrying out their intended functions efficiently throughout the spacecraft life. Owing to the need, the size of these electronics in modern spacecraft is continuously increasing, which necessitates designing them so as to have increase in its fatigue life by reducing the high stresses coming over them. The electronic packages are designed such that they should protect the inside electronic components. The use of aluminium and magnesium alloys has been quite common in fabrication of these spacecraft packages. To fulfil the needs of higher strength and increase in its fatigue life the use of Beryllium-Aluminium MMC (composed of 62% of Beryllium and 38% of aluminium, having a resistance to deformation about 50% higher than that of steel with only about 1/4$^{th}$ weight and 3 times stiffer than aluminium), have been proposed.

This paper briefly describes the use of Beryllium-Aluminium MMC (AM162), for their use in Avionics electronic package design which shows minimizing the stress levels, deflection, and increase in its natural frequency, and thereby increases in its fatigue life as compared to aluminium and magnesium alloys. The FE analysis of an electronic package, made up of different materials, has been carried out and compared for the induced stress levels, deflection and natural frequency. Based on this the fatigue life has been estimated, which shows appreciable increase in the package made up of AM162.

*The work had been* presented *at an* international conference ***Fatigue Durability India 2015**, 28-30th May 2015, JN TATA AUDITORIUM, Indian Institute of Science, Bangalore.* 

## Introduction

In the field of aerospace, electronic components play an important role, which should be protected from undesirable vibration, distortion and thermal effects. In spacecraft, these electronic components are used for control, communication, guidance, power distribution, onboard housekeeping and other payload related functions. Electronic components (such as capacitors, resistors, PCB, etc.) are quite small and sensitive to fit into the spacecraft in their operational configuration and have to be protected from harsh environment to perform their intended function[1]. The electronic packages are designed such that, they should protect these electronic components from failure in harsh environment. The design requirements of these electronic packages should meet the guidelines for strength, weight, reliability and should perform the intended function without failure. The spacecraft structures and its materials should be chosen such that they should have low density, high stiffness & strength, increased fatigue life, ease of fabrication and economical[2].

Generally, the Power packages in a spacecraft has higher packaging density and increased power dissipation. The mechanical module should be such that the stresses generated at critical locations should be well below their yield point, minimising the displacement, and increasing their fundamental frequency thereby increasing their fatigue life. The advancement in the technology has brought out new materials, design improvement and additional information about service requirements.

Since past, the use of traditional materials to achieve the required specification has been practised. As the technology progressed, the use of materials having low density and high young's modulus became popular, which met the required specifications e.g. Aluminium alloy (AL6061), Magnesium alloy (AZ31B) have been the common choice of the design engineers.

The need of high stiffness, light weight, high performance electronic power packaging for various space application has addressed several challenging issues in the selection of right material for electronic enclosure and the need of the advanced materials has been explored [3].

This paper briefly describes the advantages of the use of Beryllium-Aluminium Metal Matrix Composite MMC (AM162) for realising the electronic package so as to meet the frequency, stiffness and strength with increased fatigue life, as compared to that of AL6061 & AZ31B.

### *Selection of material*

In space applications, the selection of material, for its structural components, plays an important role. This applies not only for complex designs, but also to the simple designs and for small structures too. Proper selection of materials is always advisable to make sure that the structures will perform well in an unpredictable situation.

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In the field of electronic packaging technology, the material selection is a tedious task because there are number of factors that have to be carefully evaluated before making the final decision. The main requirement may be the strength for particular application, but depending on the working environment, its application and behaviour, several other factors may have to be considered like high frequency, low density, high young's modulus, electrical properties (like EMI, EMC etc.). First it is required to carefully define the requirements in terms of mechanical, thermal, environmental, electrical, and chemical properties. Then the choices are narrowed down by the method of elimination. Fabrication methods also have a major importance in selecting the best material.

In the selection process, materials will be assessed for high young's modulus, low density, tensile strength, flexural strength and fatigue endurance, creep, and stress-relaxation properties depending on the application. This will ensure that the design will have a better probability of success. It is also assured that the design is technically fit to obtain desired properties. A design may fail in the actual working environment when it may be subjected to a higher load than expected. It may be damaged by unexpected vibration, high induced stresses, and in these conditions, only a good design with proper material selection may survive.

The advancement in avionic technology and continuous increase in packaging density requires high young's modulus to achieve high fundamental frequency for the electronic packages keeping their weight to be minimum. Minimising the weight also reduces the stresses resulting from vibration shock loads that can occur during launch environment and service life of the spacecraft electronics. Traditional materials, such as AL6061 and AZ31B, used in electronic packaging may not meet all these requirements and hence new materials meeting the above requirements are being developed.

Spacecraft electronic packages prefer reduction in its weight and at the same time require an increase in its first fundamental frequency. This is done to decouple the frequencies of the electronic package to that of the spacecraft structural elements, such that the resonance can be avoided.

AM162 is from the family of MMC, made up principally of beryllium and aluminium. These two material ratios can vary to alter the mechanical, physical and thermal properties. The optimum composition of these two materials (62% Beryllium and 38% Aluminium) is used to achieve the desired properties better than AL6061 & AZ31B. AM162 with a density of 2100 kg/m$^3$, combined with an elastic modulus of 193GPa, provides a unique combination of mechanical properties and stiffness about 3 times that of aluminium. The following table provides the mechanical properties of AM162, AL6061 and AZ31B [4-5-6].

**Table 1**: Material properties used in Electronic Packages

| Properties/Material | Aluminium Alloy (AL6061) | Magnesium Alloy (AZ31B) | Beryllium-Aluminium (AM162) |
|---|---|---|---|
| Young's Modulus (GPa) | 72 | 46 | 193 |
| Poison's ratio | 0.33 | 0.3 | 0.17 |
| Density (kg/m$^3$) | 2780 | 1870 | 2100 |
| Ultimate Tensile strength (MPa) | 320 | 220 | 413 |
| Shear strength (MPa) | 190 | 130 | 345 |
| Coefficient of Thermal Expansion (ppm/°C) | 23.6 | 25.2 | 13.9 |

*Finite element modelling of the Power Electronic package*

The power electronic package is generated using the FE software and analysed to predict its dynamic characteristics. This will also help in assessing the reliability of the structure, and reduce the product development cost by reducing the time and design changes at a later stage. QUAD4 elements available in MSC NASTRAN/PATRAN FE software are used for generating the 2D mesh. The total numbers of quad elements in the model are 173961. The ribs, which are provided to connect printed circuit boards (PCB,) are modelled as beam elements (Bar2) and are 234 in number. All lug locations of the modules are constrained using multi point constraints (MPC) are connected by using RBE2 elements at holes for even distribution of load.

*Finite element model and Boundary conditions*

Figure 1 shows the FE model of the power package in a spacecraft. The boundary conditions (i.e. fully constrained at 8 lug locations on bottom module), applied to the model, are shown in (Fig 2).

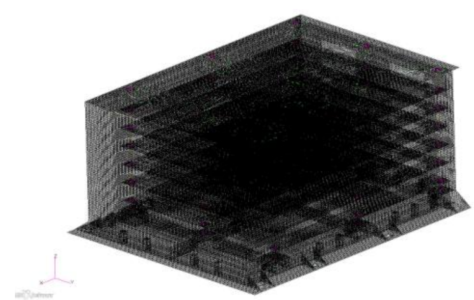

**Figure 1:** Finite Element model of Package

*Linear static analysis of the Power Electronic Package*

Finite element analysis is carried out using MSC PATRAN as pre-processor and MSC NASTRAN as solver. The FE model of the Electronic package for linear static analysis is shown in (Fig 2). All 8 lug locations are constrained by arresting all six DOFs, and 20g inertial load is applied to the package. Fine mesh with good quality elements are created in the critical locations to get better results.

Linear static analysis represents the most basic type of analysis. This is carried out to assess the mechanical strength of the package as well as to get the critical location where the maximum stress is likely to occur. It involves loads that are applied to the structure, which will not create dynamic response or steady state response. The failure of the structure is most usually associated with the yielding of the material, and the Von-Mises stress generated are compared with the yield strength of the material. Basically linear static analysis is carried out to evaluate the critical stress location in the package. Figure 2 shows the loading information applied to the package. The analysis is carried out for the different package materials i.e., AL6061, AZ31B and AM162 and presented in Table-2.

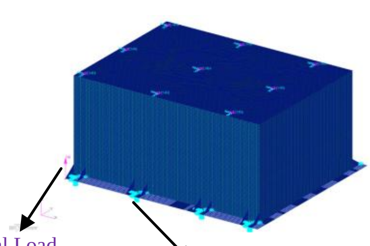


**Figure 2:** Boundary Conditions and Inertial load applied to the Package

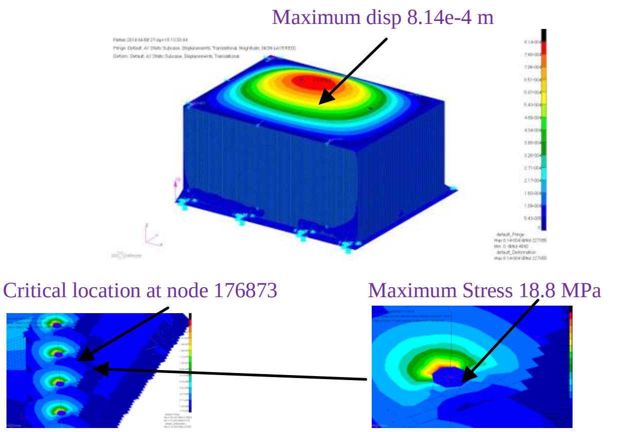


**Figure 3:** Displacement and critical location of Electronic package using AL6061 material

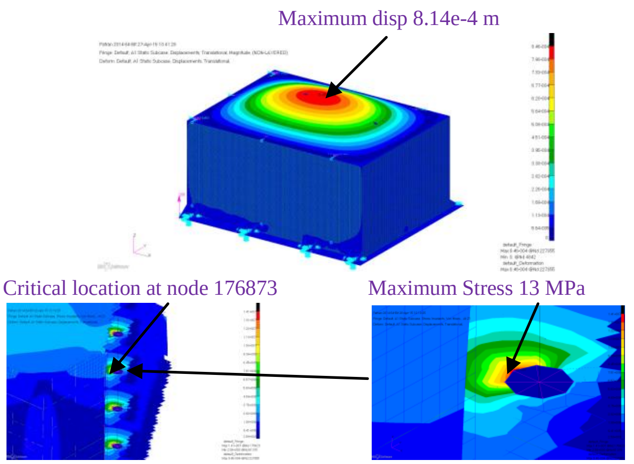


**Figure 4:** Displacement and critical location of Electronic package using AZ31B material

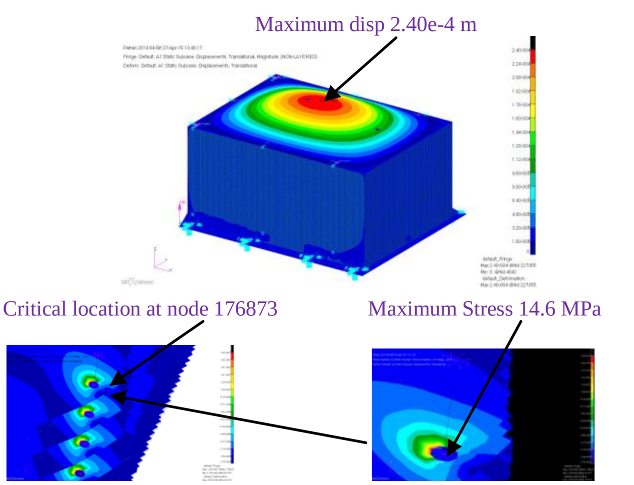


**Figure 5:** Displacement and critical location of Electronic package using AM162 material

**Table 2**: Results of the linear static analysis

| Results/Material | Aluminium Alloy (AL6061) | Magnesium Alloy (AZ31B) | Beryllium-Aluminium (AM162) |
|---|---|---|---|
| Displacement (m) | 8.14e-4 | 8.46e-4 | 2.40e-4 |
| Maximum Principal stress (MPa) | 18.8 | 13.0 | 14.6 |
| Von-Mises stress (MPa) | 20.3 | 14.1 | 16.3 |

The package modelled with AL6061 material shows the displacement as 8.14e-4 m, with a maximum stress of 18.8MPa and the Von-Mises stress with 20.3MPa at the node 176873 (Fig 3). For AZ31B material, the displacement is 8.46e-4m, maximum stress is 13MPa and Von-Mises stress is 14.1MPa at the node 176873 (Fig 4**)**. For AM162 material, the displacement is 2.40e-4m, maximum stress is 14.6MPa and the Von-Mises stress is 16.3MPa (Fig 5**)**. AM162 shows minimum displacement and has the reduced stress at the critical regions compared to other materials.

*Normal modal analysis of the Power Electronic Package*

Modal analysis is carried out to determine the dynamic characteristics of the package such as natural frequency and mode shapes of structure. The natural frequency of the structure is determined to compare the frequency of excitation to see whether the resonance exists[7]**.**

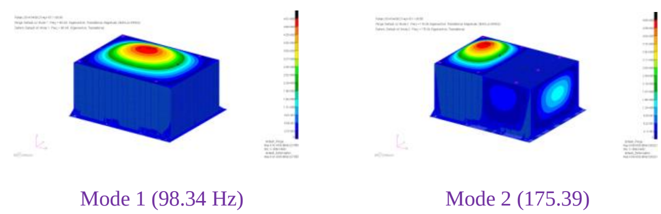


**Figure 6:** Mode shapes of Electronic Package using AL6061 material

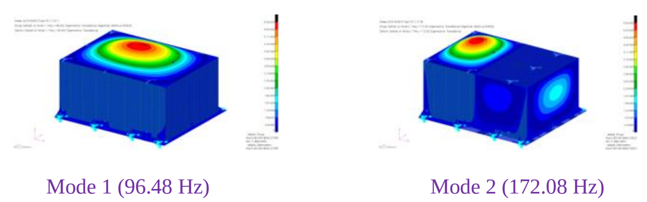


**Figure 7:** Mode shapes of Electronic Package using AZ31B material

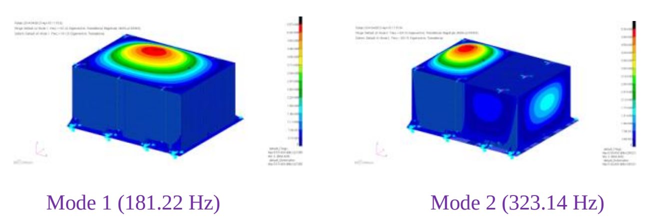


**Figure 8:** Mode shapes of Electronic Package using AZ31B material

**Table 3**: Results of the Modal analysis for different materials

| Mode No. / Material | AL6061 | AZ31B | AM162 |
|---|---|---|---|
| Mode 1 Hz | 98.34 | 96.48 | 181.22 |
| Mode 2 Hz | 175.39 | 172.08 | 323.14 |

The modal analysis results (Table-3) shows that AL6061 has its Mode-1(first fundamental frequency) at 98.34 Hz and Mode2 at 175.39 Hz (Fig 6). AZ31B has its Mode-1 at 96.48 Hz and Mode-2 at 172.08 Hz (Fig 7).

AM162 has its Mode-1(first fundamental frequency) at 181.22 Hz and Mode2 at 323.14 (Fig 8) which is higher than the respective values of the other two materials. This shows that the package made of AM162 is stiffer than that of AL6061 and AZ31B and can sustain higher dynamic loads.

*Fatigue Analysis*

Fatigue is the process of progressive localised permanent structural change, subjected to actual loading that produce fluctuating stresses and strains at critical regions which can develop the failure in the structure after sufficient number of cycles. Fatigue damage occurs in the structure due to stress concentration at the bolt hole, fillet, flange, and rivet or at tool marks. Minimising these stresses is the first step to increase the fatigue life. Material like aluminium alloy and magnesium alloy widely used in the spacecraft electronic packages do not exhibit clear fatigue limit, but has a tendency to fail at quite low stress with millions of repetitions. Spacecraft structures are subjected to fluctuating loads in its service life and are liable to fail due to fatigue. Failure mechanism by the fatigue results when the cyclic loads cause dislocation of the molecular structure. There are two methods to determine the fatigue life of the structure: stress-life and strain-life approach. The stress-life approach is used for high cycle stress fluctuations that have stresses significantly below the yield strength of the material. Whereas strain-life approach is used for both low and high cycle stress fluctuation and is recommended when stresses are near or exceeding the yield strength.

In the case of the power electronic package the fatigue analysis is carried out to understand the effect of material on its fatigue life under actual service conditions which is time dependent with variable amplitude loading. A complimentary method to increase the fatigue life of the package is selection of material, which resists the failure of structure in the critical region. In this approach, first static analysis is carried out to know the maximum stress location in the package. The critical regions (in the static analysis) are selected to estimate the fatigue life of the structure to minimise the computational time.

*Time Dependent loads*

The loads coming on the package depend, on their placement on the spacecraft structure and are generally time dependent. They may be deterministic or random in nature. After knowing the critical regions, the transient response analysis is carried out to obtain the stress- time history for variable amplitude loading. In practical situation, the package experiences repeated loading which is more sensitive than the static strength and is detrimental. However in fatigue there are inherently more stress variables such as stress amplitude, mean stress and number of repetitions of stress. The transient analysis shows more scattering in stress values and hence to determine the accurate stress amplitudes, alternating stress values, and number of cycles, the rain flow counting method is used[9-10-11].

*Stress- Life approach*

There are several methods to determine the fatigue life of the electronic packages. Stress-life method is one approach for fatigue analysis. Fatigue life depends on the geometry, material, applied load and service conditions of the package. By the stress–time history the maximum and minimum stress has been taken and thereafter the alternating stress value and the mean stress value has been calculated. The S-N curve is used as primary input, next step is to count the stress, ranges, and mean loads of the given stress-time history. Using rain flow counting method, the life is represented as S-N curve [10-11], which can be expressed as

$$S_{Nf} = \sigma'_f (2N_f)^b \quad (1)$$

where $N_f$ is the no. of cycles to failure and $S_{Nf}$ is the fully reversed fatigue strength at $2N_f$ reversals. The stress-time curves for different materials are shown in Figure-8 to 13 for 20g loading. The maximum and minimum stress ($S_{max}$ and $S_{min}$) are obtained by Rain Flow Counting method (Fig.9, 11, 13). The alternating stress ($S_a$) and mean stress ($S_m$) values are determined using $S_{max}$ and $S_{min}$.

Modified Goodman equation is used to find the $S_{Nf}$ (Eq-2). The ultimate tensile strength, true fracture strength of the material are required to determine the cycles ($S_{Nf}$) to failure[10-11].

$$\frac{S_a}{S_{Nf}} + \frac{S_m}{S_u} = 1 \quad (2)$$

*where,*
*$S_a$ = is applied alternating stress*
*$S_m$ = is Mean stress value*
*$S_u$ = is Ultimate tensile strength*

To compute damage fraction 'Palmgren-Miner rule' is used, which is expressed as [11],

$$D = \sum (n/N_f) \quad (3)$$

*where,*
*D = Damage Fraction,*
*n = number of cycles for a specific stress range,*
*$N_f$ = is the no. of cycles to failure,*

The expected fatigue life ($L_{expd}$) is calculated as the reciprocal of eq-3 [11].

$$L_{expd} = 1/D = 1/\sum (n/N_f) \quad (4)$$

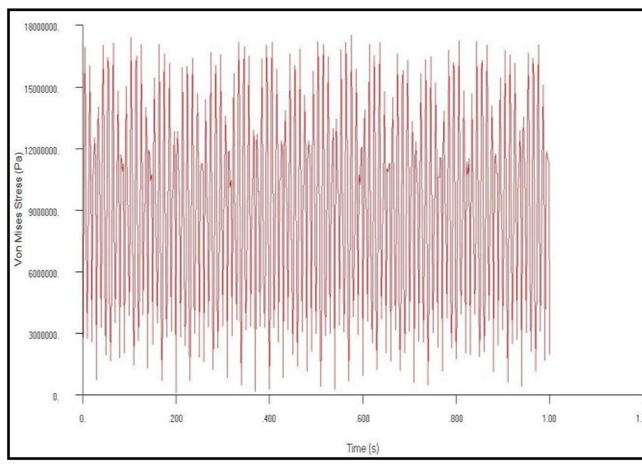


**Figure 8:** Stress-Time History for package made up of Al 6061

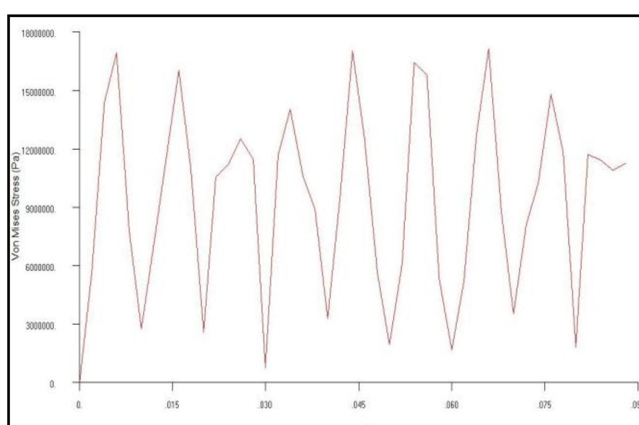


**Figure 9:** Representative blocks of Stress-Time history of Al 6061

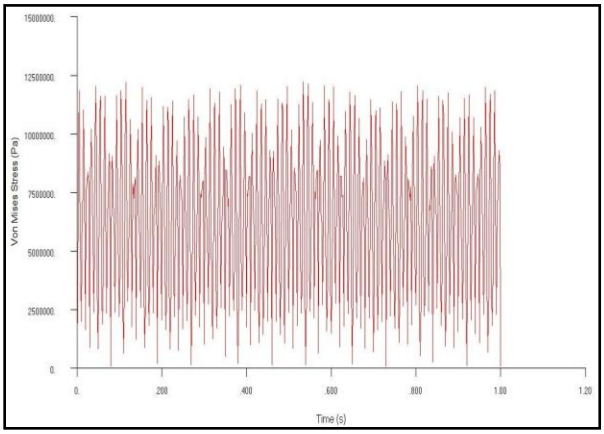


**Figure 10:** Stress-Time History for package made up of AZ31B

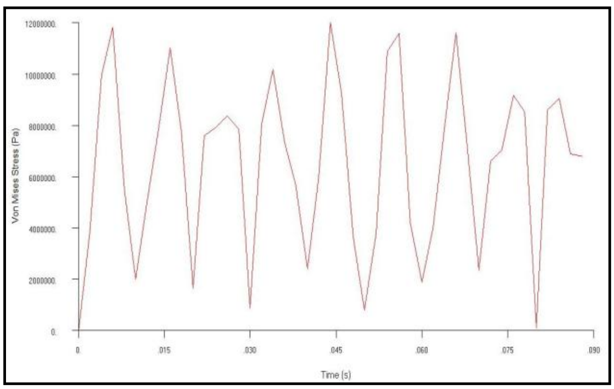


**Figure 11:** Representative blocks of Stress-Time history of Mg Alloy

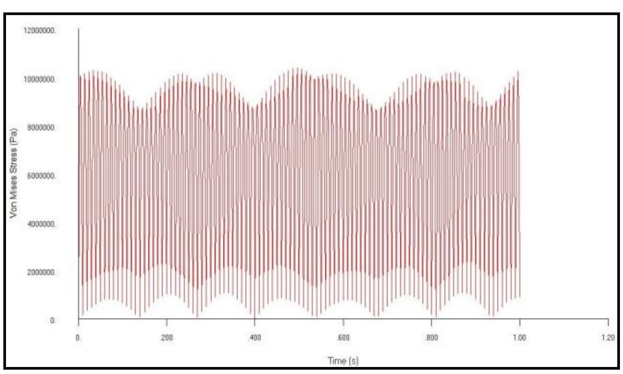


**Figure 12:** Stress-Time History for package made up of AM162

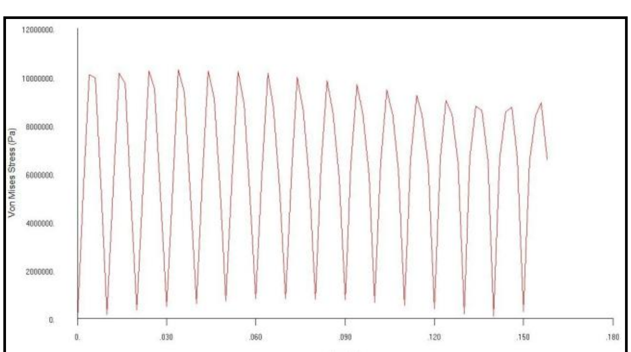


**Figure 13:** Representative blocks of Stress-Time history of AM162

The electronic package experiences severe fatigue loading for about 30 minutes during launch phase. The critical stress locations are grouped separately which are found through static analysis. Fatigue analysis is carried out only for these critical zones, by the stress-time history graph. The repeated blocks are taken for rain flow counting and $S_{max}$ and $S_{min}$ are taken to determine the fatigue life. Using Basquin's equation (Eq.1) and Modified Goodman equation (Eq.2) the fatigue life of the package is determined. The fatigue life of the package made up of AZ31B has been calculated to be 9.92e6 cycles, for package made up of AL6061 the fatigue life has been calculated to be 1.02e10 cycles. Compared to both AL6061 & AZ31B material, the fatigue life of the package made up of AM162 shows high increase in the fatigue life to be about 4.12e17 cycles.

## Conclusions

The FE linear static analysis results show that AM162 material has better strength with low displacement and reduced stresses on the critical locations of the electronic package.

Normal Modal Analysis show that the first fundamental frequency the electronic package made up of AM162 material is more than 100 Hz and this ensures that the resonance will not occur. By the use of AM162 there exists a considerable increase in the fatigue life of the electronic package as compared to that made up of AL6061 & AZ31B.

With the above observations it can be concluded that the type of material has a predominant effect on the fatigue life of the electronic package. AM162 material is a promising candidate for its use in fabrication of electronic packages, especially for inter-planetary and scientific missions.

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