Effect of Intermetallic Compound Thickness on Thermo-mechanical Reliability of Lead-free Solder Joints in Solar Cell Assembly

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ABSTRACT

The fatigue failure of lead-free SnAgCu solder joints in solar cell assembly is studied to determine the effect of thickness of intermetallic compound (IMC) layer on the reliability of the joints. Finite element modelling (FEM) is used to simulate the non-linear deformation of solder joints in crystalline silicon solar cell assembly. In this study, five geometric models of solar cell assembly with IMC thickness layer in the range of 2 to 10 μm were subjected to accelerated thermal cycling utilising IEC 61215 standard for photovoltaic panels. Creep response of each of the assembly's solder joints to the induced thermal load were simulated using Garofalo-Arrhenius creep model. Analysis of the results indicates that the thickness of IMC in the joints significantly impacts the thermo-mechanical reliability of the assembly joints. The effect is such that the mean-time-to-failure (MTTF) of the assembly depends on the thickness of the IMC layer – such that solder joint fatigue life decreases as IMC thickness increases.

***Keywords*:** solar cell assembly, lead-free solder, thermo-mechanical reliability, intermetallic compound, finite element modelling.

1. INTRODUCTION

Globally, produced photovoltaic (PV) modules are predominantly made with wafer-based crystalline silicon solar cells. In 2013, wafer-based crystalline silicon PV module consists about 90.956% of global module production [1]. There is the vital need to improve the reliability of wafer-based crystalline silicon PV modules which account for greater percentage of PV module production. The manufacturing process of wafer-based crystalline silicon PV modules involves printing silver (Ag) busbar electrode unto the front surface of solar cell. This process is followed by high temperature soldering of copper ribbon strip on the printed Ag busbar while an extended part of the ribbon strip is soldered to the back of a neighbouring cell to form a series connection. Nowadays, lead-free solder alloys such as tin-silver-copper (SAC) alloys are used for the interconnection of solar cells as a replacement of the hazardous lead-based solder alloys which were previously used. The high temperature interconnection of these solar cells results in the diffusion and metallurgical reaction between copper (Cu) and tin (Sn) elements as well as Ag and Sn elements to form intermetallic compound (IMC) layers at the interfaces. The layer of IMC formed at the interface joint between solder and copper ribbon, the IMC layer formed consists mainly of Cu_3Sn and Cu_6Sn_5 IMCs while at the Ag busbar and solder interface joint, the IMC layer consist of Ag_3Sn intermetallics [2].

During field operations, PV modules undergo thermo-mechanical fatigue loading due to thermal cycling and differences in the coefficient of thermal expansion (CTE) of the interconnect materials. The resultant thermal effect of the thermo-mechanical fatigue loading is further growth of the IMCs in the solder joint. In an experimental study, Schmitt et al [2] reported that IMCs decrease the performance and reliability of solder joints in PV modules.

Previous studies on the effect of formation and growth of IMC on reliability of solder joints in crystalline silicon solar cells include references [2], [3] and [4]. These investigations used experimental methods and also studied the effect of IMC on the mechanical strength of solder joints as well as adhesion and durability of the joints. Literature on research employing finite element modelling to study reliability of interconnection in PV modules which incorporates IMC is scarce - notwithstanding that FEM method is a valuable tool for product design and development [5]. The FEM method is used in this study to simulate the non-linear creep deformation of solder joints in crystalline silicon solar cell assembly because many researchers have employed similar method in the investigations.

This study utilises five geometric models of solar cell assemblies with different IMC thickness layers in the range of 2 to 10 μm. The models were subjected to accelerated thermal cycling from -40 °C to 85 °C utilising IEC 61215 standard for photovoltaic panels. The study evaluates the quantitative damage of the solder joints using the concept of hysteresis loop. Furthermore, the study evaluates the thermally induced creep deformation stored in solder joint as strain energy and its effects in the whole joint with IMC layer as well as in the solder region. The values of creep strain energy density were determined and used to predict the service lifetimes of the models.

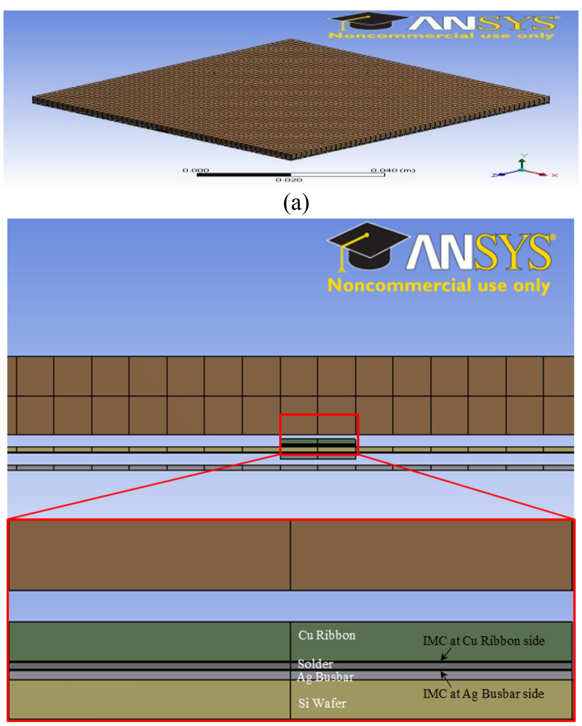
2. FINITE ELEMENT MODELLING

This section presents the discussion on finite element modelling used in this study. The discussion is presented in three sub-sections.

2.1 Model and Methodology

The study of induced strain in 156 × 156 mm^2 multi crystalline silicon solar cell assembly was carried out using commercial ANSYS academic research finite element package. The solar cell assembly has two printed Ag bus bars on its front surface and on the busbars, copper ribbon strips are soldered. Work station computers were used to carry High Performance Computation (HPC) involved in simulating the assemblies. Quarter symmetry of the geometric models were simulated to lessen modelling time and disc space. Presented in Fig. 1(a) is the meshed geometric model of the whole assembly of crystalline silicon solar cell while Fig. 1(b) shows the section of the model where components are interconnected. The static structural response of the geometric models subjected to accelerated thermal cycling utilising IEC 61215 standard for photovoltaic panels were simulated. The geometric models include IMC layers at the solder joint interfaces. In this study, five geometric models of solar cell assembly with IMC layer thickness of 2μm, 4μm, 6μm, 8μm and 10 μm were used and are assigned numbers 1, 2, 3, 4 and 5 respectively. These IMC layer thicknesses are within the range of thicknesses obtained experimentally by Schmitt et al [2] and Yang et al [4] in their studies on the formation and growth of IMC layers in silicon solar cells. Presented in Fig. 2 is a plot of IMC thickness and solder volume against model number. The whole solder joint comprises of three regions: IMC layer at the interface joint between solder and Cu ribbon; solder region; and IMC at the interface joint between solder and Ag busbar. Each model has the same volume of solder in the joint as the other model. It can be observed in Fig. 2 that as thickness of IMC layer increases from the low value in model 1 to the high value in model 5, the solder volume in the whole joint decreases accordingly.

In the analysis of simulation results, model based on whole joint is termed *model i whole joint* while model based on solder region is termed *model i solder region*. The "i" designates models 1-5 used in this study. The creep strain, stress and strain energy of whole joint models as well as solder region models are evaluated and comparatively analysed. Furthermore, accumulated creep strain energy density in the solder joints of each model was determined and compared. Moreover, the accumulated creep strain energy density in the solder joint was used for life prediction computation of the joint in each model.



(a)

(b)

Figure 1. Crystalline Si solar cell assembly showing:
(a) the meshed assembly (b) interconnected components

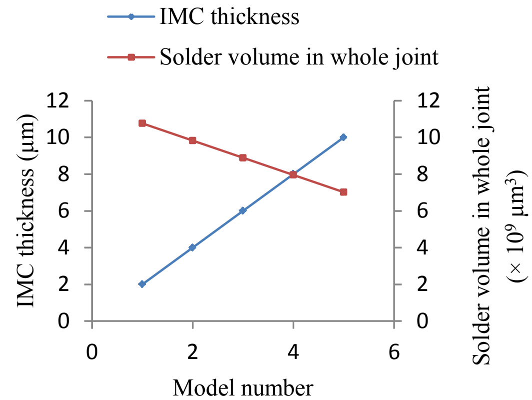


Figure 2. Plot of IMC thickness and solder volume against model number

2.2 Materials and their Properties

The solar cell assembly presented in Fig. 1 consists of various materials with dissimilar properties. The geometric model is built and assigned the component materials. The Sn-3.8Ag-0.7Cu solder material property is used in the solar cell assembly model. Other material properties used in the geometric model include Cu ribbon, Ag busbar, IMCs, Si wafer, Al rear contact and Tedlar backsheet and their properties such as Young's modulus, CTE, Poisson ratio and shear modulus are used.

2.2.1 Constitutive Solder Model

The solder joints in solar cell assemblies undergo thermo-mechanical loading during accelerated thermal cycling tests as well as in field service. The elastic and inelastic deformation behaviour of the solder alloy is described by constitutive models. One of the solder constitutive models commonly used in finite element analysis (FEA) is the Garofalo-Arrhenius creep model. Creep of a solder material is often characterized by its steady-state creep strain rate [13]. This study utilized the hyperbolic sine creep equation to simulate the creep behaviour of Sn-3.8Ag-0.7Cu solder joints. This equation in the format containing Garofalo-Arrhenius creep model constants is given by [7]:

$$\dot{\varepsilon}_{cr} = C_1[sinh(C_2\sigma)]^{C_3} exp^{-C_4/T} \qquad (1)$$

The C_1, C_2, C_3 and C_4 are creep parameters. Their values for Sn-3.8Ag-0.7Cu solder are presented in Table 1.

Table 1: Generalized Garofalo Creep Constants [14]

Constant	C_1	C_2	C_3	C_4
Units	1/sec	1/Pa	-	K
Value	2.78E+05	2.45E-08	6.41	6500

2.2.2 Fatigue Life Prediction Model

The inelastic response of solder subjected to thermo-mechanical loading is the standard method used to evaluate the fatigue life of the solder. The primary damage mechanism for SnAgCu solder during thermal cycling is creep and it is used to simulate the material behaviour. Therefore, the life prediction model has to be theoretically based on creep deformation [7].

The accumulated creep strain energy density per cycle is used to predict fatigue life of solder joints subjected to thermal cycling loading. Number of cycles to failure is given by:

$$N_f = (W'W_{acc})^{-1} \qquad (2)$$

where, N_f is number of repetitions or cycles to failure, W' is creep energy density for failure and W_{acc} is accumulated creep energy density per cycle. The constant W' has been determined experimentally as 0.0019 [7].

2.3 Loads and Boundary Conditions

The geometric models were subjected to six accelerated thermal cycling in 25 load steps between -40 °C to 85 °C utilising IEC 61215 standard for photovoltaic panels. The temperature loading started from 25 °C, ramped up at a rate of 3 °C/min to 85 °C, where it had hot dwell for 20 min. It was then ramped down to -40 °C at a rate of 6 °C/min, where it had cold dwell for 20 min. Presented in Fig. 3 is the thermal cycling profile used to simulate actual cycling profile used during thermal load test.

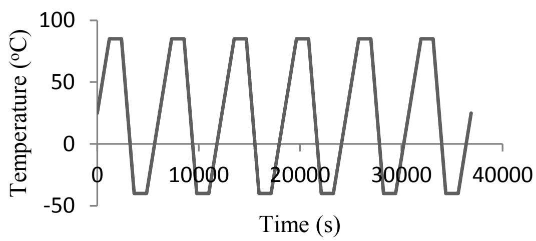


Figure 3. Plot of temperature profile of thermal load test condition used in the solar cell assembly

3. RESULTS AND DISCUSSION

This section presents analysis and discussion of results.

3.1 Evaluation of Hysteresis Loop

The damage distribution of stress and creep strain on the solder joint of *model i* is presented in Fig. 4. Presented in Fig. 4(a) is the stress in the whole joint which is similar to the stress in solder region are similar as in Fig. 4a. However, the creep strain in the whole joint (Fig. 4b) is higher than that of solder region (Fig. 4c). Presented in Fig. 5 is a plot of the relationship between stress and creep strains in the solder joints of solar cell models. The figure shows five hysteresis loops each for models of whole joint and solder region which formed as a result of thermal cycling. It can be observed that induced stress in models of whole joint is higher than in models with solder region only due to thr presence of IMCs in the whole joint.

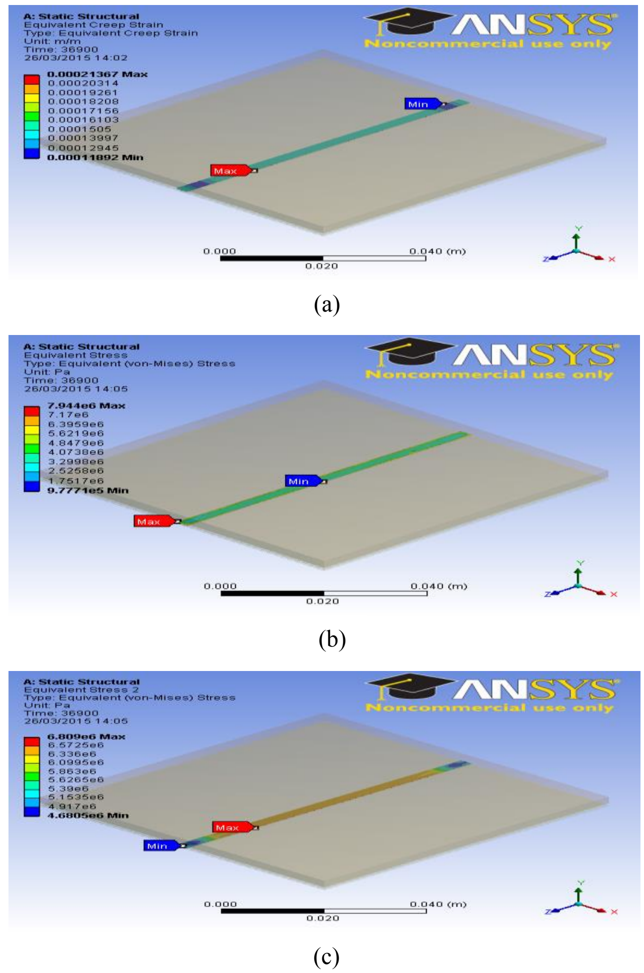


Figure 4. Damage distribution of equivalent stress and creep strain on the solder joint showing:
(a) stress on model i whole joint;
(b) strain on model i whole joint
(c) strain on model i solder region

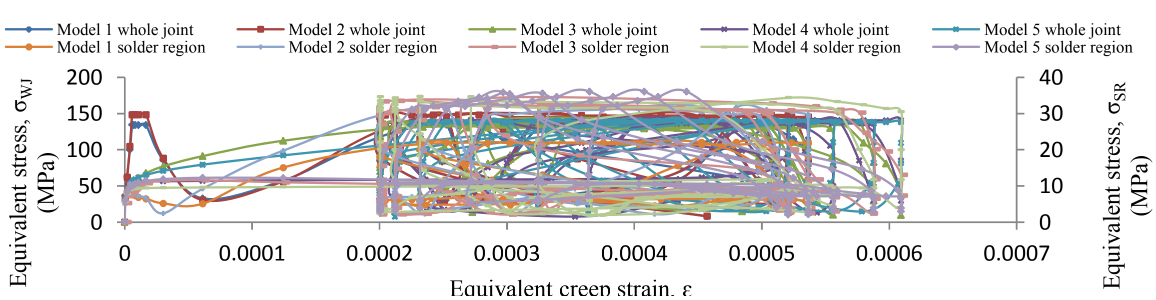
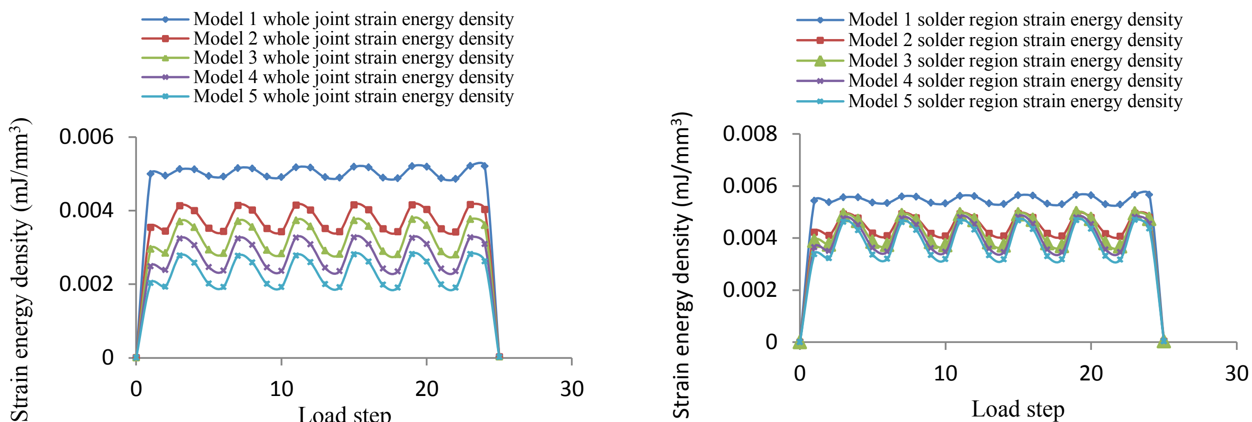


Figure 5. Relationship between stress and creep strains in the solar cell models

3.2 Study on Strain Energy and Accumulated Creep Strain Energy Density

The applied thermal load induces creep deformation in solar cell solder joint. The creep strain energy per unit volume is stated as strain energy density. Presented in Fig. 6 is a plot of accumulated strain energy density against load step. In Fig. (6a), model 1 has the highest value whereas model 5 has the least value. A similar situation occurs in Fig. 6(b) where models 1 and 5 have the highest and least values respectively. Moreover, it can be observed that accumulated strain energy density is higher in solder regions than in whole joints. This implies that the solder regions are affected by the presence of IMCs.



(a) (b)

Figure 6. Plot of strain energy density for models showing strain energy density for: (a) whole joint (b) solder region

3.3 Study on Solder Joints Life Prediction

The solar cell solder joint service life can be predicted using fatigue models such as Syed's model presented in Eq. 2. The values of accumulated strain energy density of the models are inputted into Eq. 2 to compute fatigue life of each model. The fatigue life is also stated as mean-time-to-failure (MTTF) or cycles to failure. The results of the fatigue life computation are plotted in Fig. 7. The plot shows that as solder joint fatigue life increases as IMC thickness decreases. Therefore, the MTTF of the assembly solder joints depends on the thickness of IMC layer.

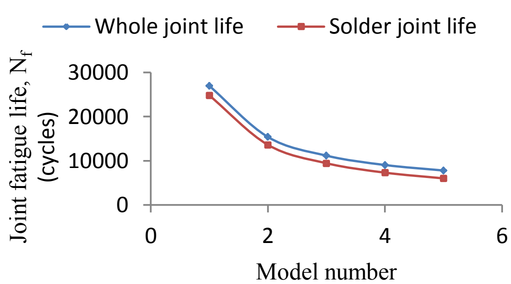


Figure7. Plot of joint fatigue life versus of model number

4. CONCLUSIONS

This study has demonstrated that hysteresis loop of the whole joint has larger area than that of solder region. It implies that creep strain energy per unit volume per cycle accumulated in the whole joint is higher than that accumulated in the solder region. Since the creep energy is a damage measurement index, the higher the energy accumulated in a joint, the higher the damage on the joint. Therefore, it can be concluded that the presence of IMC in the joint decreases its thermo-mechanical reliability. This conclusion is further strengthened and confirmed by the result of the study on fatigue life of the joints. The finding from analysis of the results demonstrates that the rate of degradation of the joints depends on the thickness of layer of IMC. It can be concluded from this result that the fatigue life of solder joints containing IMC layer decreases exponentially as the IMC thickness grows arithmetically during assembly operations.

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