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Numerical Prediction of Solder Fatigue Life in a High Power IGBT Module Using Ribbon Bonding

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Abstract

This study focused on predicting the fatigue life of an insulated gate bipolar transistor (IGBT) power module for electric locomotives. The effects of different wiring technologies, including aluminum wires, copper wires, aluminum ribbons, and copper ribbons, on solder fatigue life were investigated to meet the high power requirement of the IGBT module. The module's temperature distribution and solder fatigue behavior were investigated through coupled electro-thermo-mechanical analysis based on the finite element method. The ribbons attained a chip junction temperature that was 30° C lower than that attained with conventional round wires. The ribbons also exhibited a lower plastic strain in comparison with the wires. However, the difference in plastic strain and junction temperature among the different ribbon materials was relatively small. The ribbons also exhibited different crack propagation behaviors relative to the wires. For the wires, the cracks initiated at the outmost edge of the solder, whereas for the ribbons, the cracks grew in the solder layer beneath the ribbons. Comparison of fatigue failure areas indicated that ribbon bonding technology could substantially enhance the fatigue life of IGBT modules and be a potential candidate for high power modules.

Key words: Fatigue lifetime, Insulated gate bipolar transistor (IGBT), Numerical analysis, Ribbon, Solder fatigue

I. INTRODUCTION

Insulated gate bipolar transistors (IGBTs) offer several advantages in power semiconductor devices, such as high operating current, fast switching speed, and low switching loss. IGBTs are predominant power semiconductors used for high current applications in trains, airplanes, and electric and hybrid vehicles [1]–[3]. Recent developments have resulted in extremely demanding industrial applications, such as railway traction systems, electric locomotives, and wind power systems, which require high power densities and long power module lifetimes. Therefore, an assessment of IGBT power module reliability in terms of enduring high operation temperatures and harsh environments has become a major concern [4]–[7]. IGBT power modules generate a considerable amount of heat from the dissipation of electric power. Excessively high temperatures result in the failure of IGBT chips if they exceed their maximum junction temperature. Another main failure mechanism that limits the operating life of IGBT modules is the coefficient of thermal expansion (CTE) mismatch between the materials used in the modules [8]–[10]. Power devices using IGBT modules are made of several multilayer structures that consist of silicon chips, ceramic layers, copper, solders, and polymers, all of which have different CTEs. The mismatch between CTEs and the various elastic moduli of the materials used can cause severe thermo-mechanical stresses and make the power modules susceptible to thermo-mechanical fatigue failures that result in cracking [11], lifting off of wires [12], [13], and delamination of the interface region [14]. Therefore, interconnected parts such as wires, bonding, and solders are the most vulnerable and essential components that determine the reliability and life span of IGBT modules. Solder joint fatigue, in particular, is one of the most important failure mechanisms [15]. The solder is located between the silicon chip and the direct bond copper (DBC) module. The mismatch between the CTE of the silicon chip and the DBC

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module is much greater than that between other layers. Under cyclic thermal mechanical loading, the materials in the interface expand and contract at different rates, and the solder joint suffers damage over time. This accumulated stress/strain leads to solder fatigue. Solder fatigue leads to delamination and cracks in the solder, which in turn increases the resistance of the IGBT chip, raises the junction temperature, and accelerates the rate of solder fatigue failure [12]–[15].

Recently, 3300 V/1500 A IGBTs were introduced to the power device market as power control unit applications for electric locomotives. Electrical and thermal stress-related problems in IGBT modules are more serious than equivalent problems in lower power devices. To meet high power requirements, practitioners have resorted to the use of copper wire or ribbon technology as a replacement for the conventional low-cost aluminum wire with the objective of enhancing electrical performances in terms of reduced resistivity and capacitance [16], [17]. Experimental works regarding the electrical performances and reliability issues of the Al ribbon technology were performed by Ong et al. [18] and Lim et al. [19]. Process issues in copper ribbon bonding technology were discussed by Marenco et al. [20]. However, only a few studies have explored the effect of copper wires or ribbons on solder fatigue failure using numerical simulation in IGBT module applications. The power cycling test is widely adopted to estimate the real operational lifetime of IGBT modules operating under cyclic power environments by switching the electrical load on and off [21], [22]. The operational lifetime prediction for IGBT modules is important in the design and application of high power devices and systems.

In the present work, we investigated the effects of different wiring technologies, including copper wires, aluminum ribbons, and copper ribbons, on solder fatigue life. Electro-thermo-mechanical coupled analysis was performed to analyze heat distribution and fatigue life in a power cycling test based on the numerical finite element method (FEM). The results will serve as guidelines for replacing conventional aluminum wires with copper wires or ribbons.

II. Finite Element Model

A. Structure of the IGBT Power Module

The schematic cross-sectional structure of the IGBT power module used in this study is shown in Fig. 1. The module comprised an IGBT chip, a DBC layer, and a baseplate, which are welded by solders. The round wires or ribbons were welded to the IGBT chip, which is soldered to the DBC layer using SAC305 (Sn: 3.0 wt%, Ag: 0.5 wt%, Cu) lead-free solder. The DBC layer was composed of an aluminum nitride (AlN) ceramic layer sandwiched between two copper layers. The layer was soldered to a copper baseplate. Table 1 shows the detailed dimensions of each layer in the IGBT module. The sizes of the IGBT chip and module were 14 mm × 14 mm and 79 mm × 69 mm, respectively. Figure 2 illustrates the schematic drawings of the different wiring methods. Figure 2(a) shows a conventional round wire with a diameter of 500 μm, and Fig. 2(b) shows a 2,000 μm-thick ribbon.

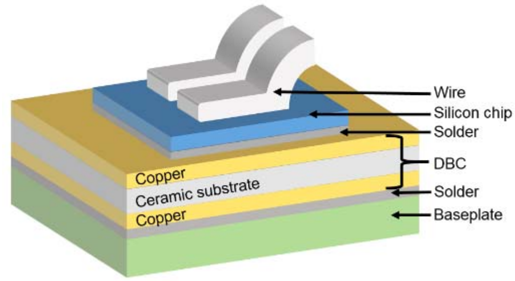
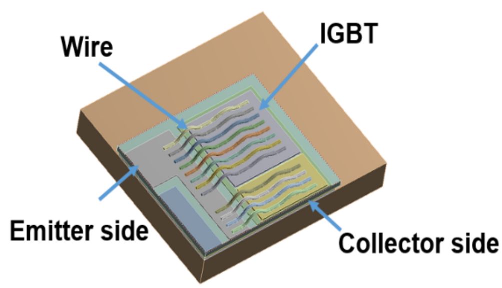


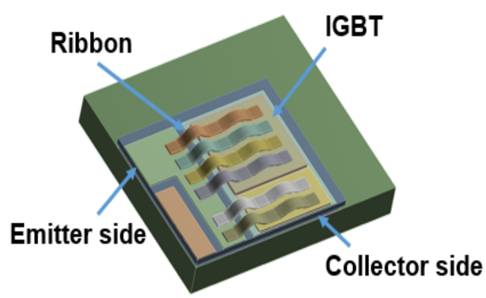
Fig. 1. Schematic drawing of the IGBT power module.

TABLE I
DIMENSIONS OF VARIOUS MATERIALS IN THE IGBT MODULE

Item	Dimension (mm)		
	Width	Length	Thickness
IGBT	14	14	0.4
Diode	14	14	0.4
Solder	14	14	0.15
Copper	54	45	0.3
Substrate	59	49	1
Copper	56	48	0.3
Solder	56	48	0.2
Base plate	79	69	5



(a)



(b)

Fig. 2. Schematic illustration of the IGBT chips and module. (a) Wire, (b) ribbon.

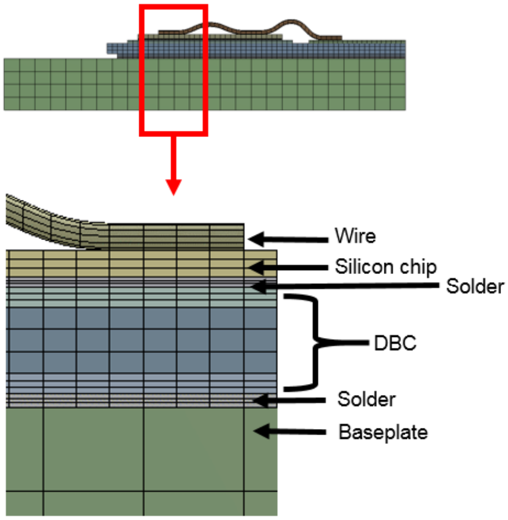


Fig. 3. FEM modeling of the IGBT power module.

TABLE II
MATERIAL PROPERTIES FOR FINITE ELEMENT ANALYSIS

Material	Young's modulus (GPa)	Poisson's ratio	CTE (ppm/K)
Silicon	186	0.22	2.6
SAC305	40	0.3	23.5
Copper	75	0.34	18
AlN	330	0.24	4.5
Aluminum	71	0.33	23
Material	**Specific heat (J/Kg·K)**	**Thermal conductivity (W/m·K)**	**Electrical resistivity (Ω·m)**
Silicon	700	148	
SAC305	232	57	1.3 e-7
Copper	385	400	1.7 e-8
AlN	740	285	1 e+14
Aluminum	875	150	2.7 e-8

TABLE III
ANAND MODEL OF SAC305

Parameter	SAC305
Initial deformation resistance (S_0)	45.9 MPa
Activation energy/Universal gas constant (Q/R)	7460 K
Pre-exponential (A)	5.87 e+6
Multiplier of stress (ξ)	2
Strain rate sensitivity of stress (m)	0.0942
Hardening/Softening constant (h_0)	9350 MPa
Coefficient for deformation resistance saturation ($\hat{S}$)	58.3 MPa
Strain rate sensitivity of saturation (n)	0.015
Strain rate sensitivity of hardening or softening (a)	1.5

B. Numerical Modeling

The commercial ANSYS program was employed for the numerical FEM simulation. The FEM structure was modeled by simplifying the actual sample. The structure was symmetric, and thus, a one-fourth symmetric model was employed for computational efficiency. The mesh of the FE model (Fig. 3) was composed of pure hexahedral elements for accurate results. The FE model comprised 575,000 nodes and 112,000 elements. The physical and thermal material properties of the IGBT module used in the numerical simulation are listed in Table 2. All materials were assumed isotropic and perfectly bonded. The silicon chip and AlN were considered elastic materials. The copper and aluminum were considered elasto-plastic materials. The yield strength and tangent modulus of aluminum were 30 and 216 MPa, respectively, and those of copper were 85 MPa and 1 GPa, respectively [20], [21]. The SAC305 solder was considered to have visco-plastic behavior using an Anand constitutive model. The Anand model comprises the inelastic strain rate and deformation resistance rate. The Anand model incorporates a visco-plastic, time-dependent plastic strain phenomenon, the development of which is dependent on loading rate [22]-[24]. This model facilitates the modeling of both strain hardening and softening. The Anand model parameters for the SAC305 solder used in this study are listed in Table III.

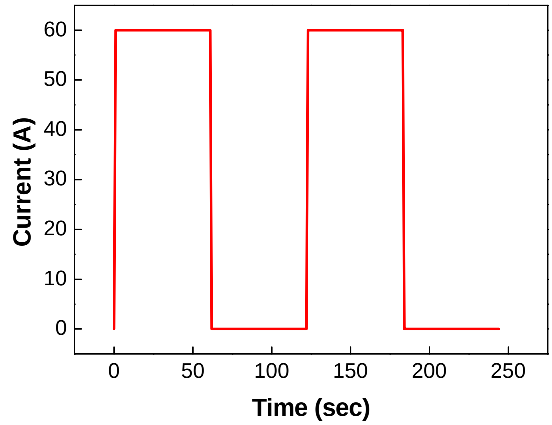


Fig. 4. Schematic of the power cycling test used in this study.

A transient multi-physics analysis (electro-thermo-mechanical coupled analysis) was performed to evaluate the thermal fatigue behavior of the IGBT module. Fatigue failure life caused by crack propagation was compared for different wiring methods. Electro-thermal analysis was conducted to calculate the joule heating distribution of the IGBT module during current loading under power cycling. The load step used for the power cycling of the analysis is shown in Fig. 4. Exactly 25 IGBT chips were used in the 3300 V/1500 A IGBT power module. Therefore, a current of 60 A was applied to a single IGBT chip. A single cycle lasted 120 s with a 50% duty ratio. The collector side boundary currents were 60.0 and 0.0 A, respectively, for 60 s during either the turn-on or turn-off state. The emitter side was set to 0.0 V. There was a 1 s ramp-up time for the switching process and a

59 s dwell time during either the turn-on or turn-off state. In the thermal analysis, the convection coefficient on the bottom of the baseplate was set to 2,000 $W/m^2 \cdot K$ after considering the heat sink effect. Except for the bottom of the module, natural convection was applied, with a convective heat transfer coefficient of 3 $W/m^2 \cdot K$. After the electro-thermal analysis, the calculated temperature was imported as a thermal load into the thermo-mechanical analysis. The thermo-mechanical analysis was conducted to predict the fatigue life of the solder layer. In the thermo-mechanical analysis, the displacement with respect to the x-, y-, and z-axes was fixed at the bottom edges of the baseplate.

III. THEORY

A. Coffin–Manson Law

Fatigue life prediction equations are usually derived in terms of strain versus the number of cycles to failure [25]. The equation consists of the elastic and plastic components of strain, and it is given by

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \quad (1)$$

where $\Delta\varepsilon_t/2$ is the total strain amplitude, $\Delta\varepsilon_e/2$ is the elastic strain amplitude, $\Delta\varepsilon_p/2$ is the plastic strain amplitude, E is Young's modulus, σ_f' is the fatigue strength coefficient, N_f is the fatigue life, ε_f' is the fatigue ductility coefficient, b is the fatigue strength exponent, and c is the fatigue ductility exponent. For a solder alloy, the empirical, strain-based Coffin–Manson equation is usually adapted to evaluate the fatigue life of the solder when the failure lies in the low cycle fatigue zone [25]. The Coffin–Manson equation is given by

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N)^c \quad (2)$$

The strain–life parameters of the SAC305 solder used in this study, such as the fatigue ductility coefficient (ε_f') and fatigue strength coefficient (σ_f'), are listed in Table 4. After calculating the plastic strain amplitude using electro-thermo-mechanical analysis, failure life (N) can be calculated using the Coffin–Manson equation.

B. Accumulative Damage Rule

After calculating the fatigue life (N) of the solder using the plastic strain amplitude, the growth of the crack on the solder was estimated using the accumulative damage rule. Miner's rule is one of the most widely used accumulative damage models for predicting failure life caused by fatigue [26], [27]. Miner's rule is a method based on damage superposition. The damage ratio for the strain range experienced in one cycle is assumed to be $1/N$, and the damage D caused by loading n times is assumed to be

$$\mathrm{D} = \frac{n}{N} \quad (3)$$

Therefore, the accumulative damage caused by different loadings can be expressed as follows

TABLE IV
STRAIN–LIFE PARAMETER OF SAC305

Constant	Parameter	SAC305
ε'_f	Fatigue ductility coefficient	0.325
c	Fatigue ductility exponent	−0.57
σ'_f	Fatigue strength coefficient	64.8
b	Fatigue strength exponent	−0.1443

$$\mathrm{D} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots + \frac{n_n}{N_n} = \sum_{i=1}^{n} \frac{n_i}{N_i} = 1 \quad (4)$$

where index i represents the phase of the crack's progress. As damage accumulates over time, D increases in value. When the damage parameter D reaches its maximum value of 1, fatigue failure of the solder occurs. In this study, the area of the solder layer is broken down into smaller segments, in which the crack propagates. These segments, each containing a number of finite element meshes, can be regarded as small, interconnected solder layers.

IV. NUMERICAL ANALYSIS RESULTS

Unlike the traditional thermal cycling test, the power cycling test involves a current flowing through a conductor with a resistance that generates joule heating, which causes rapid and non-uniform temperature distribution in the device. The IGBT chip exhibited the highest temperature, and the heat generated from the IGBT chip was dissipated in the layers underneath in a downward direction. Electro-thermal analysis was conducted to investigate the heat dissipation capacity of the round wires and ribbons. Figure 5 shows the time history of the IGBT chip's maximum temperature (or junction temperature) during power cycling. When a round wire with a diameter of 500 μm was used, the temperature of the IGBT chip reached 140° C, whereas when a 2,000 μm-thick ribbon was used, the temperature of the IGBT chip reached 110° C regardless of the materials used. The ribbon had a larger cross-sectional area than the round wire, thus indicating that the round wire had a lower current density, resulting in lower temperatures. Although copper has lower resistivity than aluminum, the temperature of the IGBT chip employing the copper wire was 1° C lower than that attained with the aluminum wire. The temperature difference between the copper ribbon and aluminum ribbon also exhibited a similar trend. This result indicates that the wire or ribbon material is not a significant factor in terms of heat generation in the IGBT power module. The maximum temperature of the IGBT chips should remain below 150° C to prevent chip failure or degradation [28], [29]. Ribbon technology is thus recommended for the safe operation of the high power IGBT module.

Heat dissipation behavior affects the characteristics of the thermal stress/strain in the IGBT module. This interaction eventually affects the fatigue life of the solder layer. After the

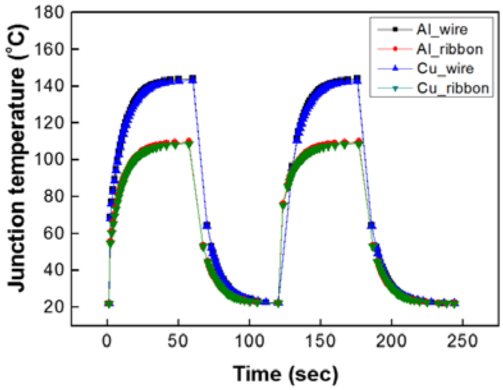


Fig. 5. Time history of the IGBT chip junction temperature during the power cycling test.

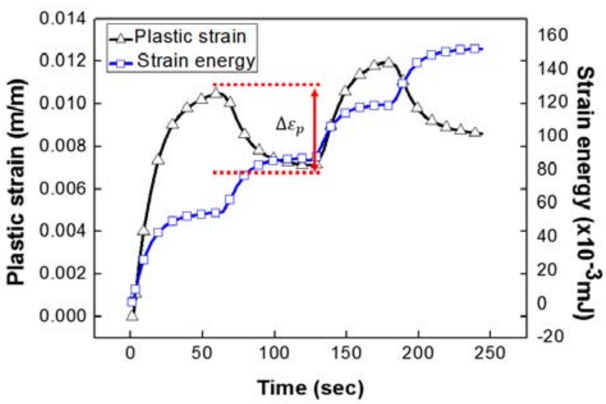


Fig. 6. Time history of the plastic strain accumulated under power cycling with the Al wire.

electro-thermal analysis, thermo-mechanical analysis was performed to analyze the solder fatigue behavior of different wire materials and ribbons. The solder fatigue lifetime was obtained with Eq. (2) by calculating the plastic strain amplitude ($\Delta\varepsilon_p$) during power cycling. The solder layer tends to accumulate stresses and strains at its comers. Therefore, cracks induced by thermal loading are expected to initiate in that region. We investigated the plastic strain and fatigue lifetime of the outermost edge of the solder layer for the aluminum wire. As shown in Fig. 6, the plastic strain and strain energy of the solder continued to accumulate during power cycling. The plastic strain amplitude of the outermost edge area of the solder was 0.0033 mm, whereas fatigue life was calculated to be 10,000 cycles. However, as the solder layer area was 14 × 14 mm^2, the fatigue life calculation for one element in a portion of one edge was considered less meaningful.

We calculated the plastic strain amplitude and fatigue life of all the elements in the solder layer and then predicted the crack propagation behavior during power cycling using Miner's accumulative damage rule. Figure 7 presents the accumulated plastic strain distribution of the solder layer after

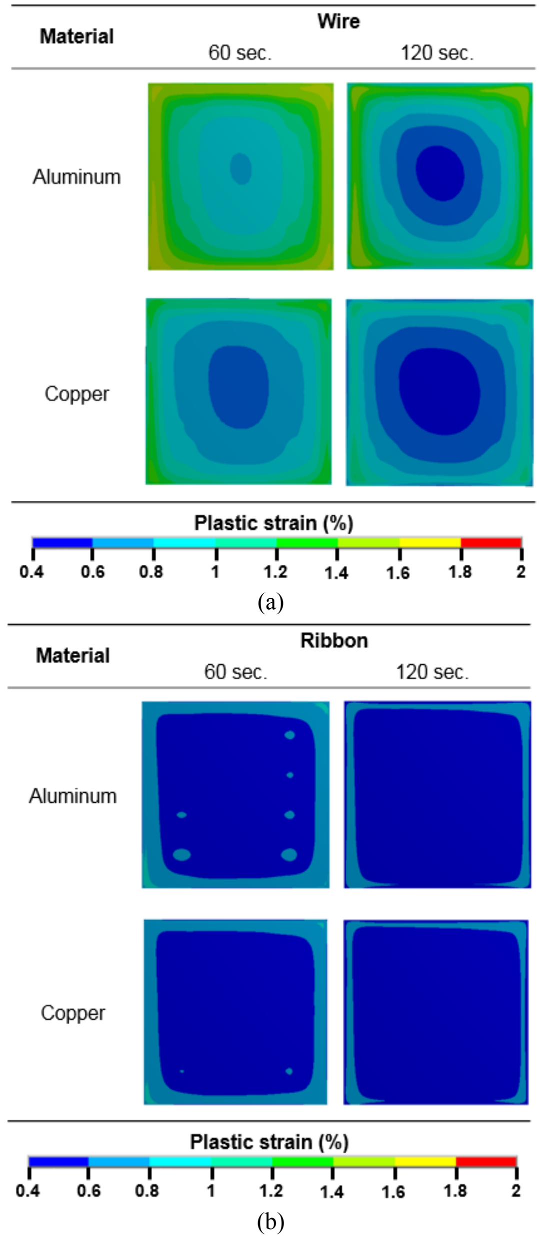


Fig. 7. Plastic strain contour map of the solder layer at 60 s and 120 s for (a) different wire materials and (b) different ribbon materials.

60 and 120 s. Figure 7(a) shows that the plastic strain in the outer corner edges for the aluminum wire reached 2% for the 60 s duration; such value was higher than that for the copper wire. Figure 7(b) indicates that ribbons showed much lower plastic strain than round wires regardless of wire materials. The differences in the plastic strains of the different ribbon materials were not significant.

After calculating the fatigue life of each element of the solder, the crack propagation images were illustrated using Miner's rule; they are shown in Figs. 8 and 9. Note that the crack propagation patterns differed according to the wire materials and ribbons. As mentioned above, cracks formed at

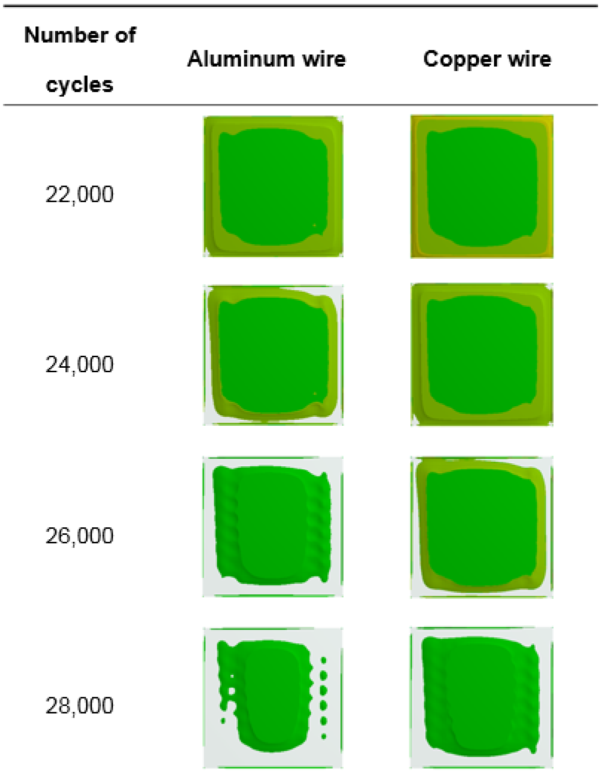


Fig. 8. Crack propagation on the solder layer for different wire materials.

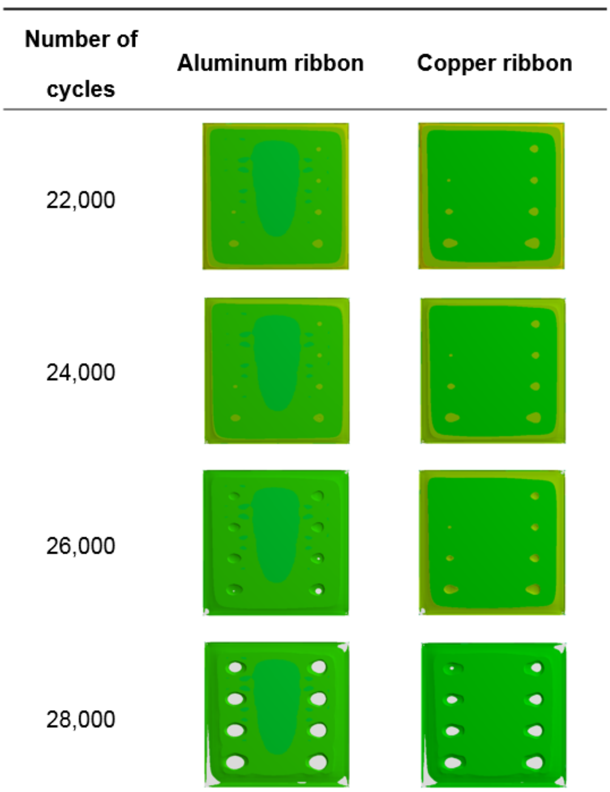


Fig. 9. Crack propagation on the solder layer for different ribbon materials.

the outermost edge for the aluminum wire. The cracked area started expanding from 22,000 cycles onward (Fig. 8). The cracked area kept increasing for the entire duration of the power cycle. The white-colored region of the figure indicates the failed or cracked area of the solder resulting from crack propagation, in which the solder no longer exists. At 28,000 cycles, the fatigue failure region became substantially large because of crack propagation, and more than half of the solder layer was cracked. Fig. 8 also indicates that the copper wire attained smaller failed or cracked areas than the aluminum wire because of the lower crack propagation speed. This result indicates that the IGBT module achieves a longer fatigue life when copper is used than when aluminum is used. Fig. 9 presents the crack propagation images for the aluminum and copper ribbons, which differ from round wires in terms of crack propagation behaviors. In the case of round wires, the cracks were initiated and then propagated from the outermost edge of the corner. In the case of the ribbons, the cracks mainly grew on the solder layer beneath the ribbons rather than on the outer edges. The solder region below the ribbons completely failed after 28,000 cycles (Fig. 9). The ribbons exhibited smaller failed areas than the round wires did, thus implying that the use of ribbon technology could enhance the fatigue life of IGBT modules. The copper ribbon achieved a slightly better fatigue life in comparison with the aluminum ribbon. In summary, in a high power IGBT module of 3300 V/1500 A, the application of ribbon technology improves reliability and fatigue life by reducing the overall heat dissipation of the chips and solder fatigue failure.

V. Conclusion

In this study, the thermal fatigue reliability of a high power IGBT module was numerically investigated using electro-thermo-mechanical coupled analysis based on FEM. The effects of aluminum wires, copper wires, aluminum ribbons, and copper ribbons on solder fatigue life were investigated. The solder fatigue behaviors during the power cycling test were analyzed. When ribbon was used, the maximum temperature of the IGBT chip was 110° C, which was 30° C lower than that attained with round wires because of the lower current density. This result indicates that ribbon technology is a good candidate for high power IGBT modules because of its safe operating temperature. However, the use of round wires or ribbons did not significantly affect heat generation in the IGBT chip. The copper wire exhibited a lower plastic strain in comparison with the aluminum wire, and the ribbons showed a much lower plastic strain than the round wires. However, the differences in the plastic strains of the different ribbon materials were not significant. The crack propagation behaviors differed according to the wire materials and ribbons. For the wires, the cracks initiated at the outermost edge of the solder. For the ribbons, cracks mainly grew on the solder layer beneath the ribbon bonding, and the cracked area of the solder layer was much smaller than that of the wire bonding. By comparing the size of the failed areas during power cycling, we found that the employment of ribbon technology could greatly improve reliability issues, such as heat dissipation and the fatigue life of IGBT power modules.

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