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Microstructure evolution of innovative thermal bridge composite (i-TBC) for power electronics during elaboration

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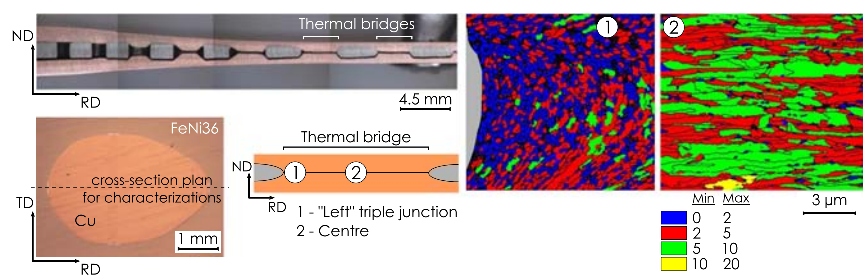
HIGHLIGHTS

- A new substrate, innovative Thermal Bridge Composite (i-TBC), for high temperature electronic systems was developed.
- i-TBC was characterized through all elaborations steps: first cold rolling, heat treatment and second cold rolling.
- Ultra-fine and coarse grained areas can be formed during the cold rolling due to heterogeneous plastic deformation.
- Interface adherence and strain hardening were found to be dependent on rolling direction.

GRAPHICAL ABSTRACT



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ABSTRACT

To improve the reliability of the power electronic modules for the high temperature applications, an innovative Thermal Bridge Composite (i-TBC) was designed. It has the architectured structure consisting of perforated FeNi36 sheet inserted between two Cu sheets. Due to simultaneous use of Cu and FeNi36, i-TBC possesses both a good thermal transverse conductivity and a limited longitudinal coefficient of thermal expansion. Different characterisations of i-TBC are required to understand the formation of its microstructure leading to the final properties. Therefore, the aim of this study was to analyse the integrity of Cu-Cu and Cu-FeNi36 interfaces as well as copper microstructure evolution throughout all elaboration steps: (i) first cold rolling, (ii) heat treatment and (iii) second cold rolling. First cold rolling did not lead to a bonding of Cu-Cu interfaces in the thermal bridge. Moreover, heterogeneity of Cu grain microstructure was observed with formation of ultra-fine grained structure close to junctions of Cu and FeNi36. The heat treatment led to a degradation of different interfaces adherence and to a complete copper recrystallization. Finally, the second cold rolling ensured an efficient solid welding of Cu-Cu interfaces and led to a heterogeneity of strain hardening of copper.

1. Introduction

A new generation of semiconductors (GaN, SiC) with a wide band gap designed for high power (>50 kW for a 0.5 cm^2 die) and high frequency (>10 MHz) applications makes possible to use the power electronic systems (modules) in harsh environments with large temperature variations (for example, from −55 to 200 °C in aircraft landing gear electronics) [1–3]. Such a temperature variation leads to a generation of thermo-mechanical stresses due to the coefficient of thermal expansion (CTE) mismatch between different materials found in power electronic modules (silicon and GaN, solders, substrate (copper and/or ceramic) and aluminium based radiator-convector) and, thus, conditions module lifetime. In addition, substrate materials based on pure

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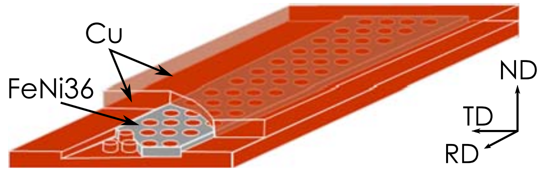

Fig. 1. Architectured structure of the i-TBC: perforated FeNi36 sheet situated between two U-shaped Cu sheets for Invar positioning.

copper are no longer compatible with the die and solder materials for such temperature cycles amplitudes and to resist these severe service conditions, the structure of power electronic modules must be redesigned, in order to minimize the CTE mismatch between successive layers.

Recently, the innovative Thermal Bridge Composite (i-TBC[1]) was proposed as a substrate material for power electronic systems [4]. i-TBC is an architectured material based on Cu and Invar™[2] FeNi36. Due to the simultaneous use of Cu and FeNi36, i-TBC possesses both a good thermal transverse conductivity and a limited longitudinal CTE. Therefore, it can provide an efficient solution for electronic packaging issues for the high temperature applications (up to 250 °C).

The architectured structure of the i-TBC is schematized in Fig. 1. The central part is reinforced by perforated FeNi36 and devoted to the positioning of active devices (semiconductors GaN, SiC); the Cu-Cu part serves for external connections and cooling through power cables. It is worth noting that both Cu sheets have initially U-shaped geometry (with thickness of 1.79/1.37/1.79 mm) to be able to place FeNi36 (initial thickness of 1.25 mm). The formation of Cu-FeNi36 interfaces ensures a reasonably low CTE of the assembly, of the order of $10 \cdot 10^{-6}\ K^{-1}$ [4], intermediate between that of Si or Si-GaN (about $4 \cdot 10^{-6}\ K^{-1}$) and that of Cu (about $18 \cdot 10^{-6}\ K^{-1}$) or Al alloys ($>20 \cdot 10^{-6}\ K^{-1}$). The main innovation of the i-TBC consists in the formation of a bond area between the Cu sheets through the perforations in FeNi36 sheet. These bond areas, called thermal bridges (Fig. 2), provide a good transverse thermal conductivity to the i-TBC from 50 $W \cdot m^{-1}\ K^{-1}$ to 250 $W \cdot m^{-1}\ K^{-1}$ [4].

The i-TBC, in terms of CTE and thermal conductivity is quite well positioned against existing alternative substrate materials although in the future composites based on copper with carbon nanotubes might be better positioned. A second originality of the i-TBC is that it can be produced as explained below, continuously by "cold" (actually up to 120 °C due to the heat generation associated with plastic deformations) roll-bonding which is a rather low cost process. To fill the perforations of the FeNi36 sheet, we have previously also considered different options like "cold spraying" of Cu powder, leading to a better Cu—Cu bond quality in the thermal bridges at the expense of a fabrication cost increase linked to the use of Cu powders and of a lower productivity than roll bonding. Hot roll bonding was not considered because of the detrimental effect of Cu oxide layers on the thermal conductivity of the bridges.

The complex architecture of the i-TBC is obtained by a succession of different fabrication steps. During each step, modifications occur in terms of the bonds quality between Cu and FeNi36 and of the microstructure. These different elaboration steps define the final i-TBC performances. Therefore, the objective of the present study is to investigate the modifications associated with each elaboration step to be able to identify the key parameters playing an important role in process leading to the final i-TBC properties.

[1] i-TBC is a registered trademark of TG-GRISET.
[2] Invar™ is a registered trademark of Aperam alloys Imphy.

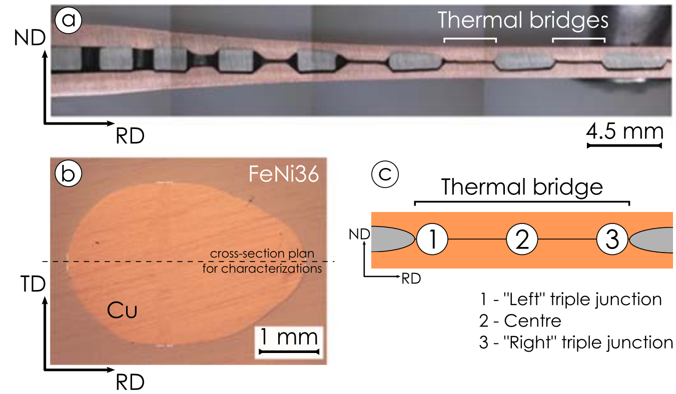

Fig. 2. Formation of thermal bridges by plastic flow of Cu in FeNi36 perforations: (a) interrupted first cold rolling; (b) top view after the second cold rolling and after polishing showing the final geometry of the thermal bridge as well as the cross-section plan for different characterizations and (c) different areas of the same thermal bridge used for characterizations carried out in the present study (see Part 3).

2. Experimental procedure

2.1. Elaboration steps of the i-TBC

A first level of optimization of i-TBC architecture was reached in a previous study [5]. Combination of 20% of surface area of thermal bridges in the FeNi36 internal layer and relative final thicknesses for two Cu and one FeNi36 sheets of 33/33/33 (%) were chosen. The final i-TBC geometry is obtained through different steps including two cold rolling that should lead to a complete filling of the FeNi36 perforations by Cu and ensure a good adherence of Cu—Cu and Cu-FeNi36 interfaces. The quality of the final i-TBC structure obtained after all elaboration steps will be further investigated and it is one of the main objectives of the present work. It is worth noting that Cu was alloyed by small additions of phosphorous and iron to form iron phosphides that should limit the Cu grain size.

Before the first cold rolling step, Cu and FeNi36 sheets are subjected to a chemical degreasing by acetone followed by wire-brushing to remove surface contamination like oxide films or dust. Further, the elaboration of the i-TBC is carried out in three steps:

1. First cold rolling step results in about 60% of thickness reduction of initial two Cu sheets and perforated FeNi36. During this step the thermal bridges are being formed by plastic flow of Cu in FeNi36 perforations (Fig. 2a);
2. Heat treatment at 450 °C for 6 h in an inert atmosphere aims to improve the ductility of i-TBC required for the second cold rolling;
3. Second cold rolling step leads to a thickness reduction of about 20% to achieve final i-TBC thickness of 1.2 mm and final geometry of thermal bridge (Fig. 2b).

All elaboration steps were carried out using industrial facilities at TG-GRISET on an existing rolling mill with 400 mm wide cylinders (while the laminates do not exceed 140 mm in width). The dimensional accuracy of the roll bonded composite can be maintained within 10 μm for the thickness (typically 1 to 1.5 mm) with short (<400 mm) and thick (>400 mm) rolls for a duo rolling mill and better accuracies are expected using a quarto. There are no serious concerns of end users with overall width (between 90 and 150 mm) as the edges can be trimmed before cutting the bands in individual substrates. Internal dimensions of both the deformed and perforated FeNi36 and of the Cu bands cannot be guaranteed with the same level of accuracy as the external dimensions of the composite band. It is worth noting, that the cold rolling steps are performed without lubrication and with a rolling rate of 10 m min^{-1}.