

Performance, Production, and Applications of Advanced Metal Diamond Composite Heat Spreader

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Abstract

Thermal management is one of the critical aspects in the design of packages for highly integrated micro-, power- and opto-electronic devices. The application of high power density electronic components such as fast microprocessors and power semiconductors is often limited by an inability to maintain the device junctions below their maximum rated operating temperature especially in multi-core architecture and the occurrence of hot-spots. The reliability of electronic components is restricted not only to operating temperature of the semiconductor component. The mismatch in the coefficient of thermal expansion (CTE) of package materials lead to critical mechanical stresses due to temperature changes during production and operation of electronic devices. Advanced metal diamond composites with Silver, Aluminum and Copper matrices exhibit high thermal conductivity (λ) in the range of 400-700 W m⁻¹ K⁻¹ and suitable CTE of about 7 – 8.9 ppm/K. A gas pressure assisted infiltration process has been developed for cost-efficient industrial production of diamond composite substrates and heat sinks. The composite microstructure and interface morphology are related to the thermal properties and represent the key to advanced composite formation. The product has reached a degree of maturity allowing the application for current and future high end applications.

Keywords: Diamond composites, heat spreader, electronics, thermal management, pressure infiltration

1. Introduction

Thermal management and thermal stresses are critical in high-power laser diode packaging, LED, and microprocessor units [1]. Reliability and long life time calls not only for high λ but also CTE matching to that of semiconductors. To use a material in electronic packaging its CTE should be compatible with that of the semiconductor, i.e CTE between 4-7 ppm/K. The trick is to use reinforcement material with lower CTE and by varying the volume fractions of the reinforcement, the CTE can be tailored to that of the specific semiconductor and application. Among all the reinforcements, diamonds are attractive as they have high thermal conductivity (1000-1500 W m⁻¹ K⁻¹ for commercially available industrial diamonds) and the ever decreasing prices bring them closer to the market realization.

Metal diamond composites have been processed

using high pressure and high temperature [2], hot pressing [3], pressureless sintering, infiltration [4, 5, 6, 7], squeeze casting and shock wave consolidation. The major challenge in any process to produce diamond composites is to produce a thin, clean, mechanically strong interface between the diamond and the metal. Most metals (except carbide formers) show poor wetting behavior with diamond and form weak or no bonds. The strength of the interface is especially important for thermal cycling and long term reliability of the semiconductor device. Silver and copper exhibit highest thermal conductivities, however have poor wetting with diamond and it is difficult to produce a bond of low thermal resistance and high mechanical strength between the matrix and the diamond in these metal matrix composites. However, this problem can be overcome by using copper or silver alloys with elements which have affinity for carbon. Aluminum on the other hand has a good affinity to carbon and readily forms

carbide, assisting in the bonding between the matrix aluminum metal and the diamond reinforcement. The present work explores the possibility of using silver, copper and aluminum alloys with elements which have affinity to diamond for producing MMCs using gas pressure assisted infiltration technique. Furthermore, the thermo-physical properties of the diamond composites are evaluated and related to the composite microstructure.

2. Experimental and Results

The diamond composites were produced by gas pressure assisted infiltration of high conductivity diamond particles with silver, copper and aluminum alloys. The quality and volume content of the diamond has a strong effect on the final thermal conductivity of the composite. The hydrogen, oxygen, and nitrogen contents were < 4 ppm, < 210 ppm, and < 250 ppm respectively. The silver and aluminum alloys investigated contain silicon additions. The copper alloys investigated in this study are a custom copper alloy with boron additions, a commercially available Cu-Si alloy and Cu-Cr alloy. The diamond particles were filled in the graphite molds to a desired final composition. The mold was heated in a vacuum furnace to above the melting temperature of the specific alloy. After infiltration the mold was furnace cooled. The infiltrated specimens from silver, aluminum and copper are shown in Figure 1, 2, 3 and 4 respectively.

The samples were characterized for density, surface roughness, λ , CTE. The sample densities were measured using the standard Archimedes density principle in accordance with ISO 3369. The surface roughness was measured using a TK100 surface analyzer in accordance with DIN 4777. CTE was measured with a Netzsch model 402 C push rod dilatometer. The samples were tested in a dynamic helium atmosphere (gas flow rate: 50 ml/min) between 10 and 160°C at a heating rate of 3 K/min. Further on, the reproducibility was checked by measuring the same sample twice. The thermal diffusivity and specific heat were measured using a Netzsch model LFA 447 *Nanoflash*TM diffusivity

apparatus. The system was calibrated with an aluminum standard prior to the sample test run.

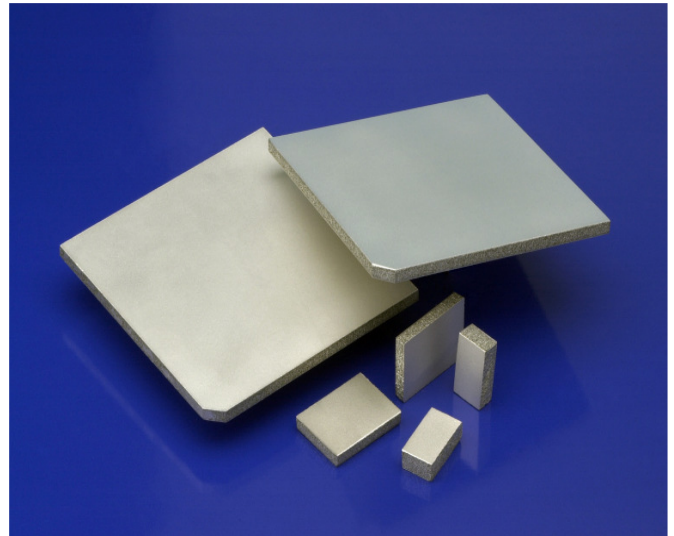


Figure 1: Gas pressure infiltrated silver diamond composites.

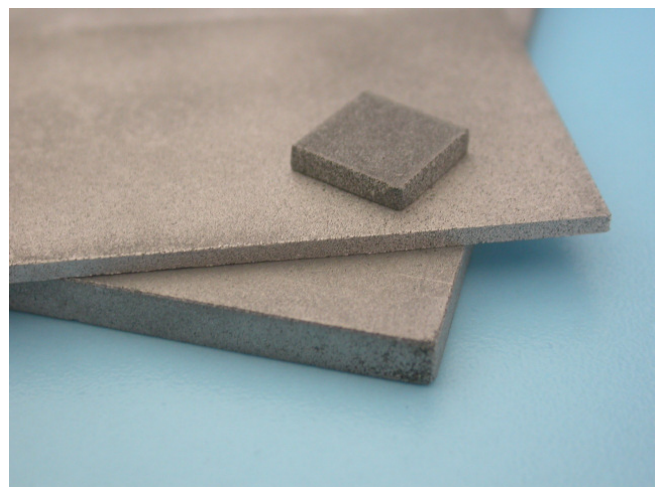


Figure 2: Gas pressure infiltrated aluminum diamond composites.

To observe the interfaces the composite was dissolved in acid solution in order to remove the metal matrix. As obtained diamond particles were dried and observed by XRD to identify the presence of phases.

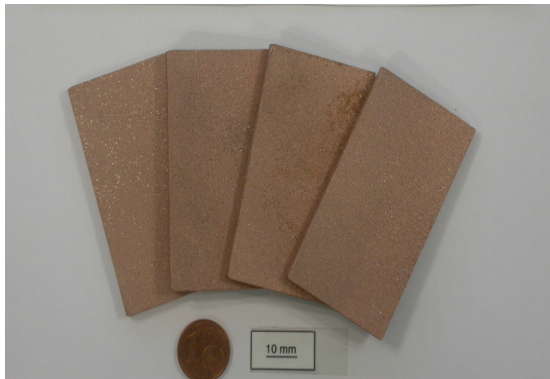
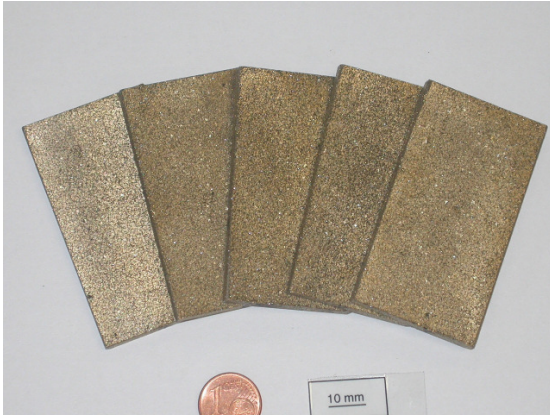


Figure 3: The above figure shows copper-diamond composite specimens. Cu-Si above and below are Cu-Cr diamond composites.



Figure 4: Gas pressure infiltrated copper boron diamond composite.

The measured data was used to calculate the thermal conductivity according to the following equation:

$$\lambda = \rho \cdot c_p \cdot \alpha \quad (1)$$

where λ is the thermal conductivity, ρ is the density, c_p is the specific heat and α is the thermal diffusivity.

The infiltrated samples exhibit near full density ($> 99\%$ of theoretical density). The surface roughness values of diamond composites show a good surface quality ($R_a \sim 4\text{-}6\mu\text{m}$). The thermal conductivity and coefficient of thermal expansion for silver diamond composites are shown in Figure 5. The thermal conductivity of the silver diamond composites is above $550 \text{ W m}^{-1} \text{ K}^{-1}$ and the CTE is $5.8\text{-}7 \text{ ppm/K}$ between 20°C and 150°C . The thermal conductivity and CTE of aluminum diamond composite is shown in Figure 6. The thermal conductivity is about $400 \text{ W m}^{-1} \text{ K}^{-1}$ and the CTE is higher in comparison to silver diamond composites with values of $7.0\text{-}9.5 \text{ ppm/K}$ between 25°C and 150°C for an aluminum diamond composite. The difference between silver diamond and aluminum diamond can be explained by considering the λ and CTE of the matrix metal. Aluminum has a lower thermal conductivity ($220 \text{ W m}^{-1} \text{ K}^{-1}$) than silver ($400 \text{ W m}^{-1} \text{ K}^{-1}$) and a higher CTE (23 ppm/K) than silver (18 ppm/K). The overall λ of the composite being dependant on the matrix conductivity, aluminum diamond composites have lower than λ and higher CTE. However, based on specific requirement of the application, aluminum diamond composites can be better suited where lower thermal conductivity is sufficient and price is a consideration.

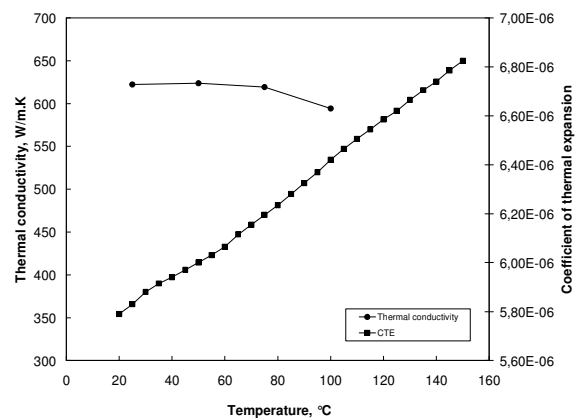


Figure 5: Thermal conductivity and coefficient of thermal expansion of silver-diamond composites.

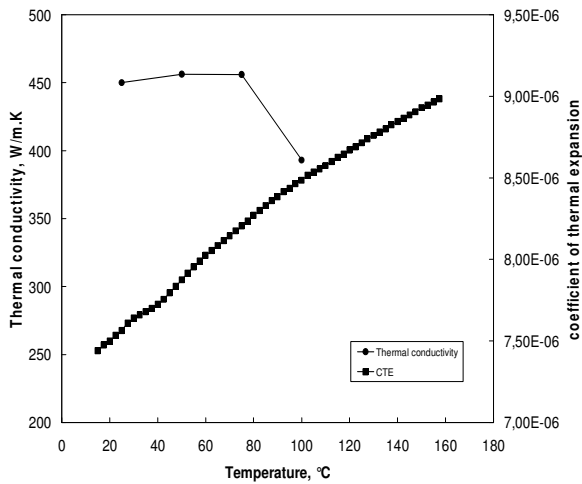


Figure 6: Thermal conductivity and coefficient of thermal expansion of aluminum-diamond composites.

concomitant increase in λ and hence an overall improvement in thermal performance of the electronic package.

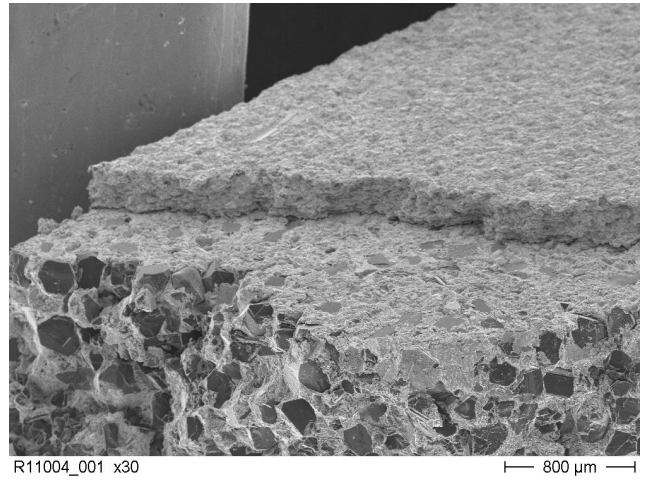


Figure 8: Fracture surface and top surface of silver diamond composite with a silver layer on top.

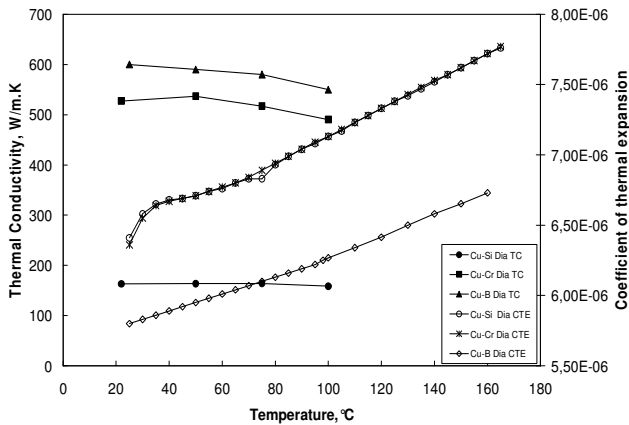


Figure 7: Thermal conductivity and coefficient of thermal expansion of copper diamond composites.

The thermal conductivity and CTE of some copper diamond composites with boron, silicon and chromium additions to the alloy are shown in Figure 7. The CTEs for copper and diamond are $16.5 - 17 \times 10^{-6} \text{ K}^{-1}$ (20-300°C) and $1.5 - 4.8 \times 10^{-6} \text{ K}^{-1}$ (127-927°C), respectively. Therefore, it is expected that the CTE of the copper diamond composite will be lowered with addition of diamond particles. The composites with boron and chromium additions have high thermal conductivity in comparison with silicon additions. The CTE is in the range of 5.5-7.5 ppm/K (25°C-160°C) which is in the range of the currently used InP and GaAs semiconductors. With higher diamond contents the CTE can be further reduced in the operating range of silicon chips, with a

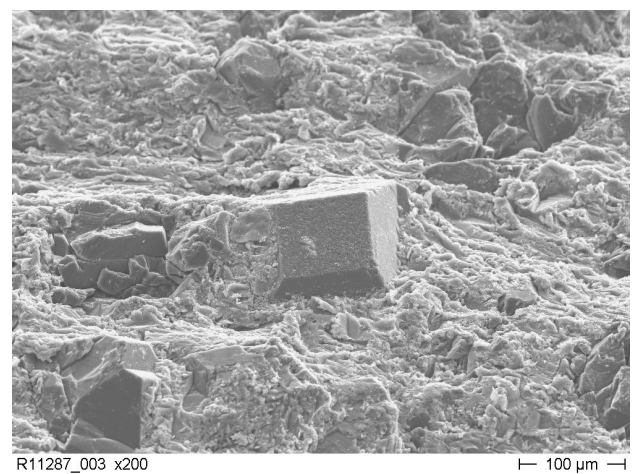
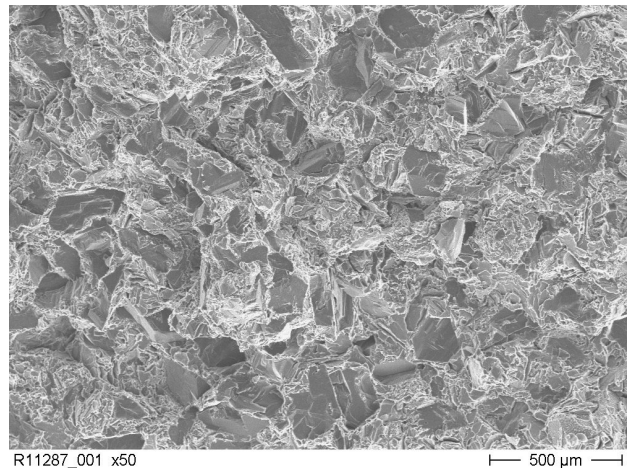


Figure 9: Fracture surfaces of Al-dia composites.

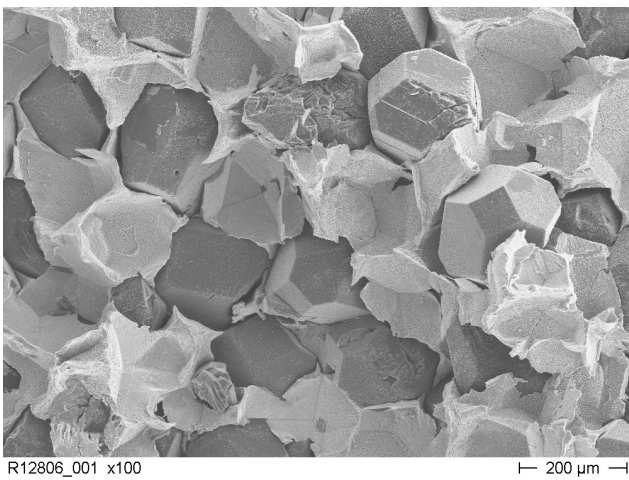
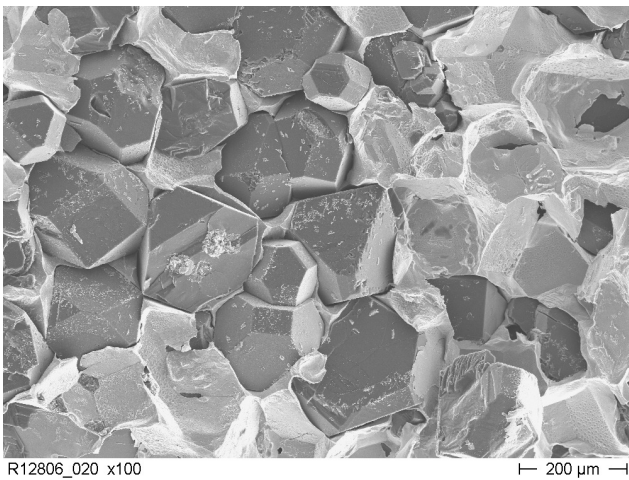
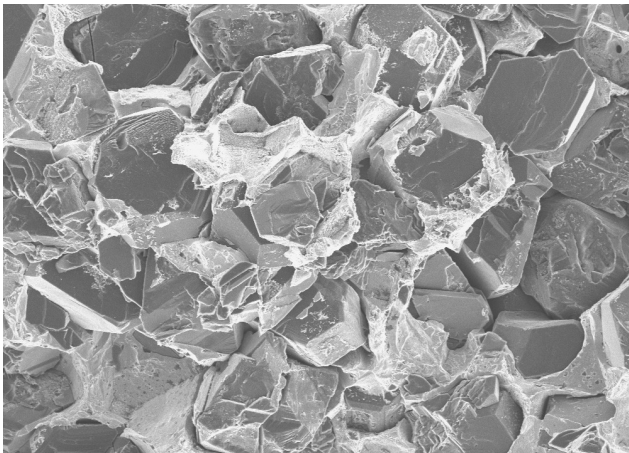


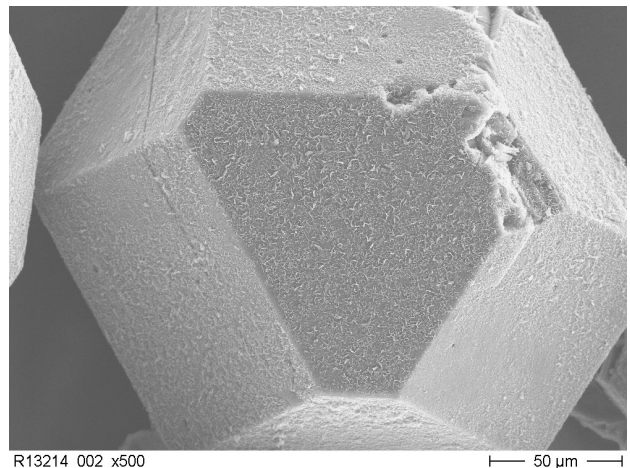
Figure 10: Fracture surfaces of Cu-B diamond, Cu-Cr diamond and Cu-Si diamond composites.

The fracture surfaces of silver diamond composites are shown in Figure 8. The fracture surfaces of aluminum diamond composites are shown in Figure 9. As seen the bonding between the matrix and the diamond particles is strong. The fracture is a combination of ductile-brittle

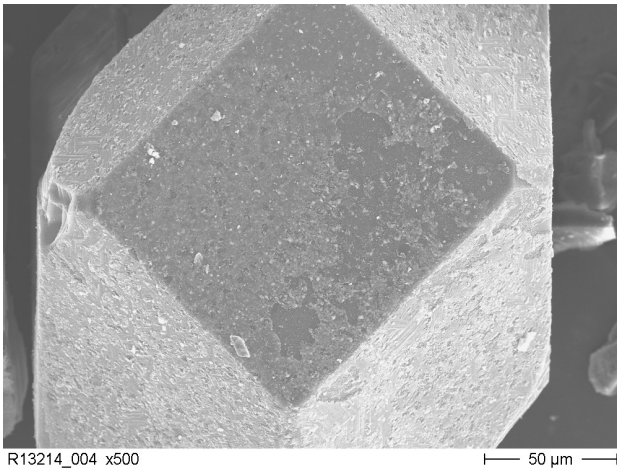
fracture, ductile in the matrix and brittle through the hard diamond particles. There is no evidence of porosity between the diamond surface and the matrix, indicating a full dense composite. The fracture modes with no evidence of diamond particle pull out suggest good interfacial bonding.

Fracture surfaces of copper diamond composites are shown in Figure 10. The fracture surfaces indicate that the fracture has propagated mostly along the carbide phase with traces through the diamond. The fracture surfaces from aluminum diamond composites look different from copper diamond composites (as seen in Figures 9 and 10). In the case of aluminum composites, aluminum reacts with diamond to form aluminum carbide. This layer is a graded layer, with diamond on one side and aluminum on the other and the fracture through this layer is different. The bonding is also stronger between the matrix and the diamond and this is seen in fracture surfaces of Figure 9. In case of carbides from silicon or other carbide formers in copper or silver diamond composites, there exists a discontinuous carbide layer at the interface. This interface is brittle and a portion of the fracture propagates through the interface.

The interfacial analysis was carried out to check the presence of carbide at the interface between diamond and the metal matrix. The composite was dissolved in an acid to remove the metal and the obtained diamond particles were dried. The diamond particles so obtained from Cu-Si diamond composite and Cu-Cr diamond composite are shown in Figure 11.



(a)



(b)

Figure 11: Diamond particles after removal of the matrix.

The as obtained diamond particles were studied using XRD, to identify the interface. The results from the XRD analysis are shown in Figure 12.

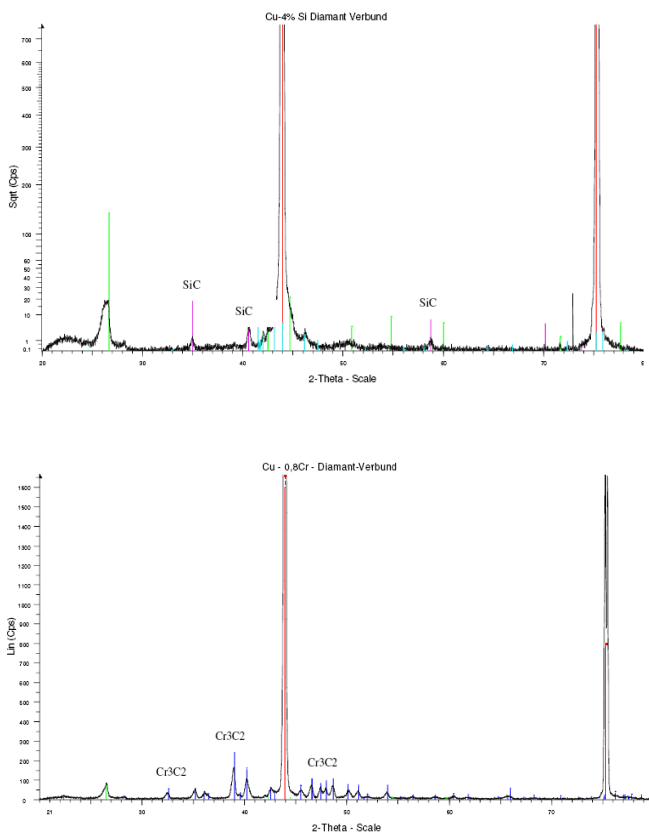


Figure 12: XRD analysis of the diamond particles after dissolution of the metal matrix.

As seen from the analysis, peaks of SiC and chrome carbide were identified. This is clear indication that the alloying additions with affinity to carbon react with diamond to form a carbide layer. A good bond between the matrix and the diamond particles is necessary for the thermal stability of the composites in operation. The thickness of this carbide layer was not determined. Thickness of the interface has an important role in the heat transfer between the diamond and the matrix.

3. Summary

Ag-, Al-, Cu- diamond composites possessing high λ ($400-700 \text{ W m}^{-1} \text{ K}^{-1}$) and tailored CTE ($5-10 \text{ ppm/K}$) diamond composites can be manufactured economically on industrial scale using gas pressure infiltration technique. Alloying additions such as boron silicon, chromium effect the formation of a mechanically strong and thermally conductive interface between the diamond and the matrix. An optimum amount of interfacial phase is necessary for sufficient thermal transfer across the interface. The thickness of the interfacial layer and its effect on composite thermal conductivity will be investigated in the future.

4. References

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