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I.E. Monje, E. Louis, J.M. Molina

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**ON CRITICAL ASPECTS OF INFILTRATED Al/DIAMOND COMPOSITES
FOR THERMAL MANAGEMENT: DIAMOND QUALITY VS PROCESSING
CONDITIONS**

I.E. Monje^a, E. Louis^{a,b,c}, J.M. Molina^{a,d*}

^a Instituto Universitario de Materiales de Alicante, Universidad de Alicante, Ap. 99, E-03080, Alicante, Spain

^b Departamento de Física Aplicada, Universidad de Alicante, Ap. 99, E-03080 Alicante, Spain

^c Unidad Asociada del Consejo Superior de Investigación Científicas, Universidad de Alicante, Ap. 99, E-03080 Alicante, Spain

^d Departamento de Química Inorgánica, Universidad de Alicante, Ap. 99, E-03080 Alicante, Spain

* To Whom Correspondence Should be Addressed

E-mail: jmmj@ua.es

Tel: +34 965 90 34 00 ext. 2055

Fax: +34 965 90 34 64

Abstract

Al/diamond composites containing diamond particles of different qualities have been manufactured by gas pressure-assisted metal infiltration and characterized by thermal conductivity (TC) measurements. The results show that the intrinsic thermal conductivity of diamond (varied with the diamond quality) plays a minor role on TC. TC is mainly governed by the Al-diamond interface characteristics, which are determined by a proper control exerted through processing conditions. Albeit a very low cost and low quality diamond is used, a high value of 667 W/mK has been measured for Al/diamond composites produced under optimized processing conditions. Values above 740 W/mK are reported for the best diamond quality explored in this work. These experimental results, which assign the control over TC mainly to the interface conductance, suggest that many of the limiting values of TC reported in literature for the different explored metal-diamond systems, need to be reconsidered by proper precise control of interface evolution.

Keywords: A. Metal-matrix composites (MMCs); B. Interface/interphase; B. Thermal properties; E. Liquid metal infiltration

1. Introduction

Metal-diamond composites have become nowadays the most considered option for current and future heat-sinking applications in electronics. These composites, which are preferentially fabricated via gas pressure-assisted liquid metal infiltration, are known to exhibit excellent thermal properties [1-9]. Their thermal expansion coefficient, which is

mainly determined by the volume fraction of present phases, can be tailored to desired values (4-5 ppm/K) for many metal-diamond combinations. In particular, an extremely low value of 3.1 ppm/K has been reported for composites containing Ag-3wt%Si and a 76 vol% of a bimodal distribution of diamond particles [9]. Their thermal conductivity (TC), which needs to be as high as possible, seems to be the key property to be optimized in order to situate these materials as the best candidates to solve the ever-growing requirements imposed by thermal management applications [9;12].

Thermal conductivity is dependent on many variables concerning nature of phases and interfacial thermal connectivity between phases. In the aim of achieving the highest possible thermal conductivity value in metal/diamond composites, research groups have based their activities on exploring the effects of different variables like metal alloying, diamond volume fraction and the use of different processing routes. In this sense, some authors have varied the metal composition by adding carbide-forming active elements like B or Cr in small amounts (<10 at%). Materials prepared by liquid metal infiltration with Cu-B exhibited optimized results of >700 W/mK [10]. When Si is incorporated into Al (Al-Si alloys), both Si and Al can act as carbide formers with the diamond particles. However, even for concentrations for which SiC is thermodynamically more stable than Al₄C₃, SiC cannot be detected and the reason for that must therefore be due to kinetic factors. Silicon, which mainly remains in metallic solution, has a detrimental effect on the thermal conductivity of the composites. As a prove, Ruch et al. [13] measured 670 W/mK for diamond-based composites with Al 99,99% matrix and, instead, 375 W/mK when matrix was replaced by Al-7wt%Si.

Another explored option has been to increase the diamond volume relative content with the use of diamond particles of two (bimodal) or more (multimodal) largely different

mean sizes, for which thermal conductivities up to 970 W/mK in Ag-3wt%Si matrix and 76 vol% diamond particles have been reported [9].

Processing conditions have been demonstrated to be very important at the level of interface quality and metallurgical conditions. An interesting body of research has been devoted to compare composites fabricated by pressure-assisted methods such as squeeze casting and gas-pressure infiltration [13-15]. Squeeze cast Al-7wt%Si/diamond composites, for which metal was rapidly solidified, exhibited lower thermal conductivities than those obtained with gas pressure-assisted infiltration [13]. Those authors already concluded that contact time between the liquid metal and diamond promoted interfacial bonding relying on partition of the elements involved within the interface layer. Other authors have explored diamond-based materials processed through vacuum hot pressing methods finding values of thermal conductivity in the range 320-567 W/mK, depending on sintering temperature and time [16;17]. Values ranging from 400 W/mK to 550 W/mK were achieved for the Al/diamond system by spark plasma processing [18;19]. The effect of diamond surface characteristics on the thermal conductance of the diamond-metal interface and the thermal conductivity of the final composite materials has also been proved to be important. Oxygenated diamond samples have roughly thermal interface conductance with Al four times higher than hydrogen-treated samples [20]. Different metallic coatings have been used to effectively increase the interfacial thermal conductance [21-23]. While some of the progresses detailed above are ultimately positive, some authors have identified the need of enhancing the intrinsic thermal conductivity of the diamond as the most promising direction of progress [9].

Very recent studies attempting to be exhaustive enough about interface characteristics are those published by the authors of the present work in which it was identified the

effect of processing conditions on the thermal conductivity of aluminum/diamond composites fabricated by means of gas-pressure infiltration [24;25]. The non-monotonic behaviour of TC versus contact time, which reached a maximum of 680 W/mK, was qualitatively explained in terms of carbon diffusion into liquid aluminum and nucleation and growth of aluminum carbide at the aluminum-diamond interface.

On the basis of those studies the authors explore in the present work the combined effects of diamond quality and processing conditions on the thermal conductivity of Al/diamond composites prepared by gas pressure infiltration. It is proved that diamond quality plays a minor role on TC, while processing conditions, that control interface characteristics, are determinant in order to optimize TC. In consequence, there is a first issue technologically important: diamond of low quality, and hence of lower price, can be used for high performance materials. A second conclusion, important from a basic standpoint, is that the values reported in literature for the different metal/diamond systems seem not to have been subjected to a careful study of interface characteristics and, hence, would need to be revised for assessing the real thermal limitations on its use in thermal management.

2. Experimental procedures

2.1 Materials

High purity aluminum (99.999 wt%), supplied by Goodfellow Metals, Cambridge, UK, was used throughout the experiments of the present work. Preforms were made out of saw-quality diamond particles of 40/50 mesh and nominal qualities ISD1300, ISD1700 and IPDSU, supplied by ILJIN Diamond (Korea). Table 1 gathers their main characteristics in terms of size distribution and relative commercial price, while Fig. 1 shows SEM micrographs at two different magnifications for each type of diamond

particles. Particles of low ISD1300 quality show sharp irregular edges probably caused by particle breaking during manufacturing. ISD1700 and IPDSU show, on the contrary, almost perfect truncated cubo-octahedral shapes. These shaping characteristics, together with their thermal stability and strength, determine the quality (and hence, price) of those types of diamond particles.

Table 1

Figure 1

Shape characterization of diamond particles was carried out with the help of image analysis (Buehler–Omnimet) coupled to an Olympus PME-3 optical microscope. In doing so, at least a minimum number of 25 microstructural images of single diamond particles were taken. Discrimination of image fields was done by colouring the images with a software based on a grey-scale threshold criterion.

Additional characterization was carried out by means of DRIFT (Diffuse Reflectance Infrared Fourier Transform) spectroscopy. For this sake, a Jasco Fourier Transform IR-4100 Instrument equipment, with a spectral resolution of 4 cm^{-1} , was employed.

2.2 Fabrication of Al/diamond composites

Diamond particles were packed into crucibles following the wet packing technique described in [26]; in the present case, it was carried out using mixtures of particles:ethanol in a weight ratio of 15:1. The volume fractions attained by diamond particles in the preforms were of 0.62 ± 0.02 for ISD1700 and IPDSU and slightly lower (0.61 ± 0.02) for ISD1300, most probably due to the less regular geometry of the latter particles. To assess as accurately as possible the effect of diamond quality, a crucible that allowed infiltrating three samples under similar conditions, was designed. Three

cylindrical cavities of 36 mm height and 12.1 mm in diameter were drilled into a graphite cylindrical block of dimensions of 40 mm height and 38 mm in diameter, parallel to the block axis and symmetrically placed. These cavities acted as crucibles allowing to infiltrate simultaneously the three samples.

A major difficulty in handling diamond-based materials is that standard machining, drilling, etc, operations cannot be performed. Thus, in order to facilitate the placement of the thermocouples needed for thermal conductivity measurements, two small holes in the radial direction were machined 4 mm apart from each crucible end, into which pencil leads 0.9 mm in diameter were introduced 5 mm into the crucible space. The inner surface of the crucibles was coated with BN-based spray to facilitate demolding.

Preforms of diamond particles packed into the crucibles described above, were infiltrated with liquid aluminum by means of a gas pressure infiltration technique [24-26]. A solid piece of the metal was placed on top of the preform and, prior to melting, vacuum was applied in order to facilitate infiltration and reduce porosity. Then, the temperature was increased up to the chosen infiltration temperature (760°C or 850°C in present experiments) and argon was introduced into the chamber until a pressure of 5 bars was reached. The infiltration process was carried out using a small pressure chamber designed for these experiments. The device allowed a rapid cooling and, thus, a rather accurate measurement of the contact time. Contact time is defined as the time during which diamond particles are in contact with the liquid metal. Temperature was controlled by means of two thermocouples inside the chamber.

2.3. Characterization of Al/diamond composites

The thermal conductivity of the composites was measured by means of a relative steady-state (equal-flow) technique, in an experimental setup assembled at the

laboratories of the Universidad de Alicante [29;30]. The cylindrical-shaped composite sample was placed in contact with a cold base (through which a flux of room temperature water is circulating) and a reference block (high purity copper 99.9998 wt%) of the same dimensions through their circular bases. The reference block was connected to a stabilized hot water bath at 70°C. The temperature gradients in the sample and the reference block, measured by means of two thermocouples in each of their respective ends, allowed determining the TC of the sample. The estimated error in TC was $\pm 3\%$.

The Al–diamond interface was characterized by means of its thermal conductance h (W/m²K). This parameter was derived for every sample from fittings of its experimental thermal conductivity with the Differential Effective Medium (DEM) approach [31-33]. For simplicity, ISD1300, ISD1700 and IPDSU diamond particles can be treated as spheres (see morphological details in the next section). For the case of composites with spherical reinforcements, the DEM approach can be simplified to give the thermal conductivity of the composite K_c in an implicit form:

$$(1 - V_p) = \frac{(K_p^{eff} / K_m) - (K_c / K_m)}{(K_p^{eff} / K_m) - 1} \left(\frac{K_c}{K_m} \right)^{-\frac{1}{3}} \quad (1)$$

where V_p is the particle volume fraction, K_m the thermal conductivity of aluminum and K_p^{eff} the effective thermal conductivity of the diamond particles:

$$K_p^{eff} = \frac{K_p}{1 + \frac{K_p}{D \cdot h}} \quad (2)$$

from which h can be derived. In applying Eq. (1), the following values for the variables were used: D given in Table 1, V_p of 0.62 (ISD1700 and IPDSU) or 0.61 (ISD1300),

$K_m=237$ W/mK, and K_p equal to the values derived for each diamond quality, which are detailed in the next section.

3. Results and discussion

3.1 *Diamond particles characterization*

Main shape characteristics of diamond particles are gathered in Table 2. The three qualities refer to particles with a high degree of sphericity; ISD1300 has the lowest value most probably because some particles are broken (see Figure 1). Aspect ratio and Feret diameter are very similar for the three qualities, except for the ISD1700, which has a Feret diameter slightly smaller.

Table 2

The presence of impurities is another characteristic that differentiates the three qualities of diamond particles studied in this work (Table 3). Impurities do influence the intrinsic thermal conductivity of the diamond since the phonon propagation, which is the main heat transport mechanism in diamond, is greatly affected. The most important impurity that is commonly found in HPHT synthetic diamond is substitutional nitrogen, or alternatively called “C centres”, which is believed to mainly determine its intrinsic thermal conductivity. The concentration of substitutional nitrogen atoms (N_c) can be calculated as the coefficient of absorption at 1135 cm^{-1} in a FTIR spectrum multiplied by a factor of 25. For this to be done, spectrum normalization is normally carried out by considering that the strength of the intrinsic absorption of the diamond lattice at a wavenumber of 1995 cm^{-1} is 12.3 [34]. However, to be more accurate, we better followed the formula established by [35] wherein absorption intensities at 1130 cm^{-1}

and the dip at 2120 cm^{-1} are considered. Figure 2 shows the FTIR spectra of diamond particles of the three qualities here studied.

The intrinsic thermal conductivity for each of the diamond qualities have been derived by replacing the encountered N_c in the correlation between N_c and thermal conductivity reported by Yamamoto et al. [36]. Derived values are collected in Table 3, which also shows a qualitative analysis of their metallic impurities obtained by means of X-ray microfluorescence spectrometry.

Figure 2

Table 3

The ISD1300 diamond quality exhibits the lowest thermal conductivity while ISD1700, being not the most expensive diamond quality, is the one with the highest intrinsic thermal conductivity. The presence of Fe, Ni and Cu in trace amounts could be due to the fact that these metals are used as catalysers for diamond growing in their manufacturing.

3.2 *Thermal conductivity for Al/diamond composites*

The results of TC versus contact time are gathered in Figure 3 for the different diamond qualities at an infiltration temperature of 760°C . Sample-to-sample variability was less than 2%. For a given diamond quality it is observed a non-monothonic behaviour of TC versus contact time, as it was previously found in [25]. The maximum value of TC at 760°C , which is 688 W/mK , corresponds to the ISD1700 quality particles for a processing contact time of about 5 min. For a given diamond quality, nil (0 min) or long

contact times (45 min) give rise to much lower values of thermal conductivity, compared to those obtained for optimized conditions. Given that Al-diamond is a reactive system, contact time between liquid aluminum and diamond particles determines a certain evolution of chemical conditions at the interface. There is a maximum value of TC that correlates with a certain degree of diffused C into Al and the appearance of crystalline precipitates at the interface that have been identified as Al_4C_3 phase [25]. In this sense, those manufacturing processes based on liquid metal infiltration in which metal is rapidly solidified (i.e. squeeze casting) or those for which Al-diamond contact time normally exceeds some tens of minutes (i.e. drain casting) are definitely not appropriate in order to obtain enhanced thermal properties in the Al/diamond system (this is in accordance with the results presented in [13;14] for Al/diamond composites processed by squeeze casting and gas pressure infiltration techniques).

Figure 3

A technologically important feature that comes out from Figure 3 is that diamond quality plays a minor role over TC compared to the contact time. Composites fabricated with ISD1300 particles have a TC systematically below those containing ISD1700 or IPDSU diamond particles, for which TC is very close. However, the difference in TC derived from diamond quality particles is, at the most, less than 80 W/mK for the whole range of contact times explored. On the other hand, we observe in Fig. 3 that for a given

diamond quality, the composite fabricated may vary its TC over a range of more than 200 W/mK depending on contact time during liquid metal pressure infiltration.

Figure 4

Similar experiments have been performed at 850°C in order to explore the effect of temperature. For 850°C, the non-monotonic behaviour of Figure 3 has been again encountered. In this case, there is an optimum contact time of about 0.75 min for which the thermal conductivity reaches a maximum of 746 W/mK when dealing with IPDSU quality particles. This value is one of the highest reported in literature for the Al/diamond system containing a volume fraction of diamond of about 0.62 (monomodal distribution of diamond particles). For the sake of comparison, Figure 4 gathers the thermal conductivity of the different Al/diamond systems for the three diamond quality particles and the two temperatures explored (760°C and 850°C) at different times: 0 min, optimum time (5-8 min for 760°C and 0.75 min for 850°C) and 45 min.

Figure 3 and Figure 4 demonstrate that it is possible to achieve a proper control over thermal conductivity in the Al/diamond system. This possibility of ranging TC with processing conditions allows manufacturing high performance materials along with a reduction of the raw materials costs. The solution encountered for many research groups in order to enhance TC of metal-diamond composites consisting of using expensive alloys like Cu-Cr or mixing different types of diamond particles while keeping the diamond quality as high as possible, have not yet attracted much industrial interest, given the inherent difficulties in manufacturing or the high costs of the raw materials. These results bring, in consequence, a new frontier for industries interested in commercialising metal-diamond composites for heat sink applications given that the

raw material cost of such composites can be lowered and performance can be tailored to desire. However, in the use of these composites in specific applications, several issues are still necessary to be clarified [11], specially those related with their stability under particular atmospheric conditions due to the presence of Al_4C_3 , which is highly hygroscopic.

3.3 Interfacial thermal conductance for the Al/diamond system

With the data at hand and making use of the DEM model for the thermal conductivity of composites with relatively high volume fraction of reinforcement phase (Equation 1 and Equation 2), the interfacial thermal conductance (h parameter in Equation 2) was back-calculated for every processing condition (Figure 5).

Figure 5

Since the changes in thermal conductivity among samples processed at different conditions have been ascribed to modifications at the Al-diamond interface, it sounds reasonable that the interfacial thermal conductance follows a non-monotonic behaviour with contact time, as the thermal conductivity does. At this point, it is worth commenting that, by looking at the present results, a single value of thermal conductance does not define, *per se*, a reactive system like Al/diamond, unless a rigorous explanation of the processing conditions is precisely given. There has been many publications by diverse research groups aiming to offer, based on physical calculations or supported by experimental measurements, the most appropriate value of thermal conductance for the Al-diamond interface, in all cases overlooking that this value cannot be unique because it strongly depends on processing conditions. Figure 6

shows a compilation of the thermal conductance values reported in literature for the Al/diamond system, along with the range of values found in this work for the temperatures and contact times here investigated.

Figure 6

Experimental determinations of this parameter for the Al-diamond interface were carried out by [37;38]. In [38], the samples were prepared by aluminum deposition onto (100) surfaces of diamond (purchased from General Electric) by either electron beam or resistive evaporation. The thermal conductance for these specific interface preparation was measured using picosecond optical techniques to be 48×10^6 W/m²K at room temperature. Monachon et al. performed measurements by time domain thermoreflectance onto (111) and (100) oriented diamond substrates (MWS L25 diamond and MD111/11 diamond, respectively, purchased from Element 6, Shannon, Ireland) prepared by aluminum sputter deposition. They concluded that for diamond substrates in the as-received condition (this is, chemically randomly terminated) the thermal conductance is around 28×10^6 W/m²K at room temperature. The authors estimated, with the approach followed in [39], a value of 33×10^6 W/m²K for particulate aluminum/diamond composites produced with variously sized powders infiltrated with aluminum. This value is significantly lower compared to that of [38]. The high value reported in [38], obtained for an ideal aluminum-diamond interface free of reaction products, coincides (within error) with the maximum value found in the present work, obtained for processing conditions of gas pressure infiltration at 850°C and 0.75 min of contact time. The values published in [13] were obtained from a back-calculation with the Hasselman-Johnson model for Al/diamond composites fabricated by either squeeze

casting or gas pressure infiltration (diamond quality was of MBD4 grade, purchased from Henan Famous Industrial Diamond Co., Ltd.). Their results – $1,6 \times 10^6$ W/m²K for squeeze cast composites and 184×10^6 W/m²K for composites processed by gas pressure infiltration – already pointed out that the formation of Al₄C₃ might in fact be desirable in order to obtain interfacial bonding between aluminum and diamond. Beffort et al. [14] reported exactly the same value of $1,6 \times 10^6$ W/m²K for Al/diamond squeeze cast composites. The value of 184×10^6 W/m²K found in [13] with a back-calculation with the Hasselman-Johnson model for composites obtained by gas pressure infiltration is an outstanding value which finds no comparison in the literature. However, we shall here take into account that the Hasselman-Johnson model may introduce artefacts in the predictions of thermal conductivity when the effective phase contrast between the matrix and inclusion is above four (which is the case for Al/diamond composites)[40]. By redoing the calculation with the DEM model and the experimental results in [13] a value of 83 W/m²K can be found, which is still above any other value published up to now. Chu et al. [41], who provided a theoretical value of 21×10^6 W/m²K calculated with the acoustic mismatch model, estimated with a double effective-medium approach scheme the thermal conductances for (111) and (100) diamond orientations based on the experiments of [13]. An exceedingly high value of the thermal conductance for (100) was explained in terms of particle-to-particle (percolation) conduction. The theoretical work of [42] assumed values for the thermal conductances of the (111) and (100) diamond surfaces of 100×10^6 W/m²K and 10×10^6 W/m²K, respectively. The assumption was based on the experimental observation of [13;14] that the higher reactivity of the (100) faces of diamond leads to enhanced bonding and to a higher interfacial thermal conductance (although reactive selectivity has been questioned in [24]). Considering these values and a ratio of (111) to (100) specific surfaces of around 3 for the diamond

particles used in the present work, a thermal conductance of 25×10^6 W/m²K can be deduced. Furthermore, Nogales et al. [43] assumed a value of 100×10^6 W/m²K for the thermal conductance of the (100) diamond surfaces and five times less for the (111) facets. Assuming these values and the ratio of surfaces for our particles we thus deduce a value of 34×10^6 W/m²K.

As a corollary of these comments on Figure 6, it is apparently clear that the Al/diamond system presents a rich interface phenomenology, which is manifested in the diverse values of thermal conductance (and interface-dependent properties) that have been found by different research groups. This is why here a sharp cutting edge advertisement shall be done on this respect: when dealing with composites based on reactive systems, there is no meaning in giving a single value of thermal conductance (hence, thermal conductivity) obtained at certain conditions as the value characterizing the system, since this value will vary with the exact processing conditions of the material. This affects many of the reported values of TC and h , that had the aim of exploring the technical limitations of those composites, like Al-diamond, with a certain interest in heat sinking for thermal management applications.

4. Conclusions

In conclusion, this study presents experimental evidence of the minor influence that diamond quality does have on the thermal conductivity of metal-diamond composites processed by gas pressure-assisted liquid metal infiltration compared to the role played by processing conditions. The control key for the TC of these composites lies on metal-diamond interface chemical interactions, which may be properly controlled by optimization of contact time and temperature during their processing. With these results at hand another important conclusion comes to light: there is a need to reconsider the

values of thermal conductivity and interfacial thermal conductance published in literature with the aim of exploring the potential limits of different metal-diamond systems. The interface conductance of any reactive metal/diamond system (like the Al/diamond system here studied), which mainly determines the final thermal conductivity of its composites, is strongly influenced by the conditions used for the processing of the material. In consequence, a unique value of thermal conductance or thermal conductivity do not characterize, *per se*, any of the reactive metal/diamond systems, except a careful and systematic study on how these parameters evolve with processing conditions is accompanied.

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Figure captions

Figure 1. Micrographs of diamond particles of qualities ISD1300 (a,b), ISD1700 (c,d) and IPDSU (e,f).

Figure 2. Diffuse Reflectance Infrared Fourier Transform (DRIFT) spectra for the diamond particles studied in this work.

Figure 3. Thermal conductivity versus Al-diamond contact time in gas pressure infiltration for different diamond qualities (ISD1300-triangles, ISD1700-circles and IPDSU-squares) at an infiltration temperature of 760°C. Lines are guides to the eye. Error bars (6%) are omitted for clarity.

Figure 4. Thermal conductivity of Al/diamond composites processed at different Al-diamond contact times (0 min, optimum time and 45 min) in liquid pressure infiltration for different diamond qualities (ISD1300, ISD1700 and IPDSU) at two infiltration temperatures (760°C – dark grey - and 850°C – light grey). Optimum times are: 5-8 min at 760°C and 0.75 min at 850°C. Error bars (6%) are also drawn.

Figure 5. Back-calculated interfacial thermal conductance with the DEM model for the Al/diamond composites (ISD1300-triangles, ISD1700-circles and IPDSU-squares) processed in this work at two temperatures (760°C-filled symbols and 850°C-empty symbols) and different contact times. Lines are guides to

the eye. For 850°C only the values presented in Fig. 4 for nil time, optimum contact time and 45 min are given.

Figure 6. Interfacial thermal conductance (h) values reported in literature for the Al/diamond system compared with the range of values found in this work. (■) Refers to measurements by the Time Domain Thermoreflectance (TDTR) technique; (●) corresponds to calculated values by the Acoustic Mismatch Model (AMM); (▲) and (▼) are calculated values from composite materials fabricated via gas pressure infiltration and squeeze casting, respectively; (◆) refers to calculated values by assuming different h for the two main diamond crystallographic facets.

Tables

Diamond quality	D	D(90)	D(10)	Span	Relative price
ISD1300	394	480	326	0.38	1
ISD1700	395	472	333	0.35	2.2
IPDSU	409	481	349	0.32	3.2

Table 1. Characteristics of the diamond particles used in this work, corresponding to qualities ISD1300, ISD1700 and IPDSU. All particles are of 40/50 mesh nominal size. Span is defined as $D(90)-D(10)/D(50)$, where $D(x)$ represents the diameter below which $x\%$ of particles are encountered. Relative price (in accordance to ILJIN Diamond) is also included.

Diamond quality	Sphericity	Aspect ratio	Feret diameter (μm)
ISD1300	0.82	1.27	402
	(0.04)	(0.09)	(36)
ISD1700	0.85	1.15	380
	(0.02)	(0.04)	(29)
IPDSU	0.86	1.15	414
	(0.02)	(0.05)	(40)

Table 2. Shape characteristics of diamond particles of qualities ISD1300, ISD1700 and IPDSU obtained with the help of image analysis. Sphericity is defined as $(4 \cdot \pi \cdot \text{area}) / (\text{perimeter}^2)$; Feret diameter is the average diameter of particles measured in all directions; Aspect ratio is the ratio between the longest Feret and the shortest Feret in the same object. Standard deviation, calculated from a population of more than 25 samples, appears in brackets below each mean value.

Diamond quality	N _c (ppm)	K _p (W/mK)	Metallic impurities
ISD1300	234	1441	Fe, Ni
ISD1700	183	1608	Fe
IPDSU	203	1543	Fe, Ni, Cu

Table 3. Concentration of substitutional nitrogen atoms N_c and derived intrinsic thermal conductivity of ISD1300, ISD1700 and IPDSU diamond particles. Metallic impurities detected by X-ray microfluorescence spectrometry are also indicated.

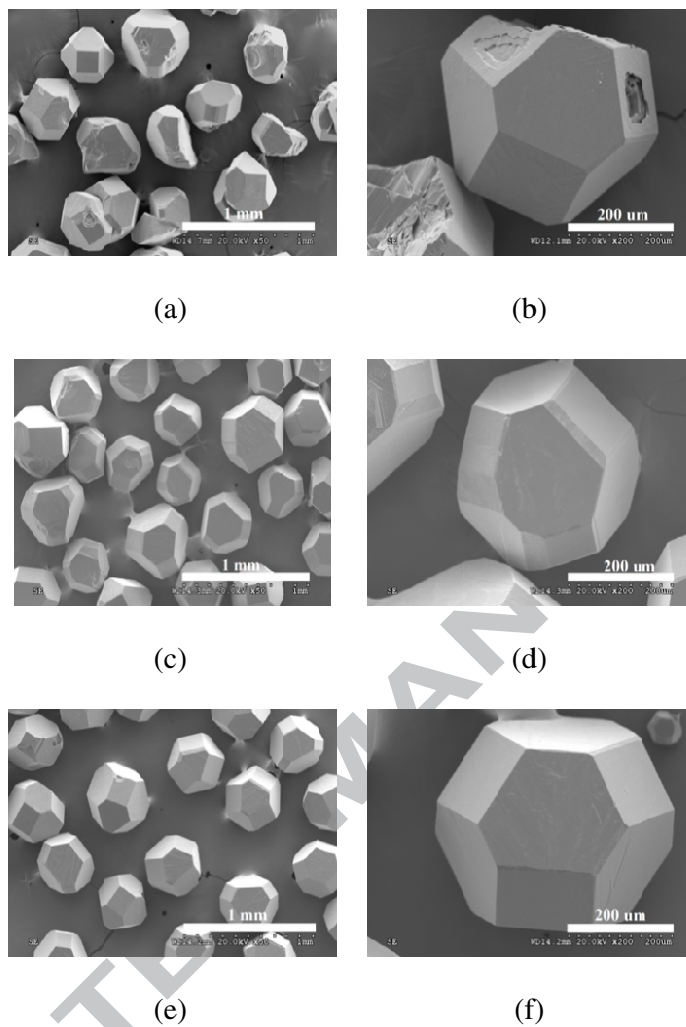


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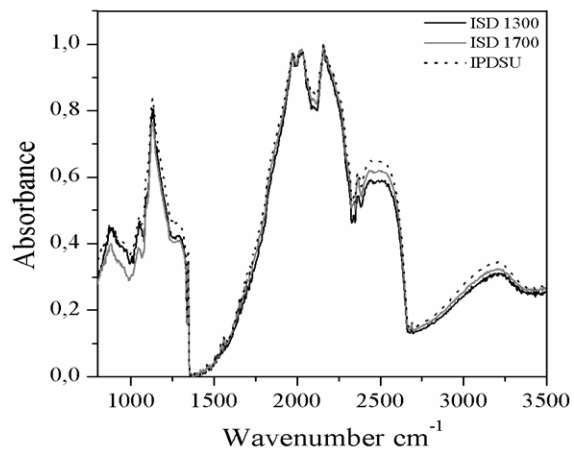


Figure 2. Diffuse Reflectance Infrared Fourier Transform (DRIFT) spectra for the diamond particles studied in this work.

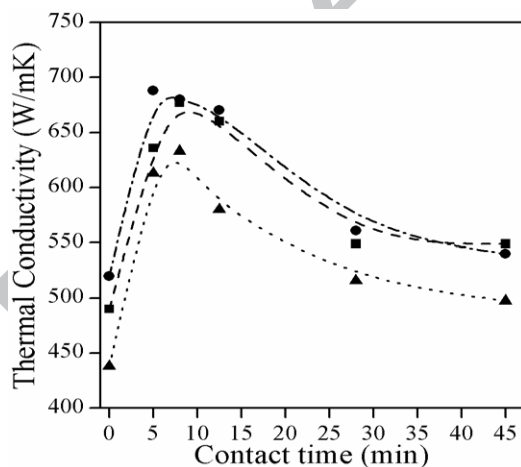


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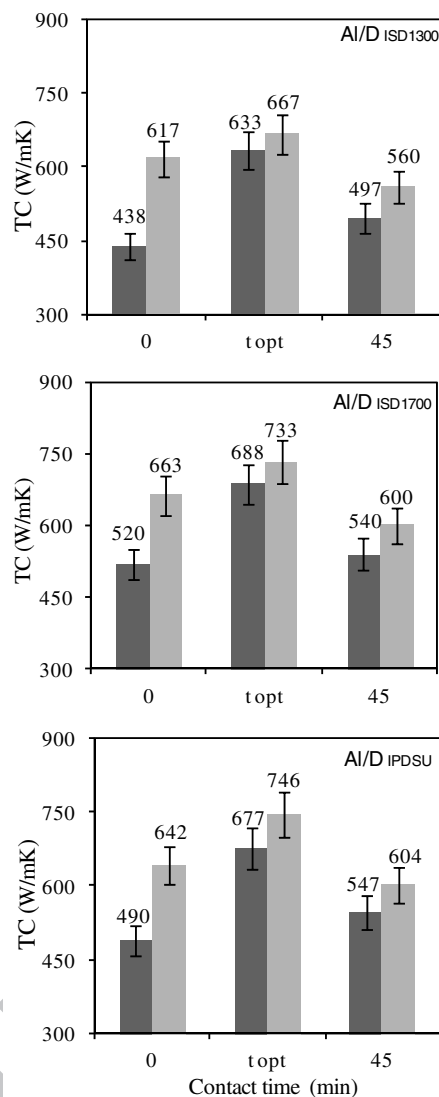


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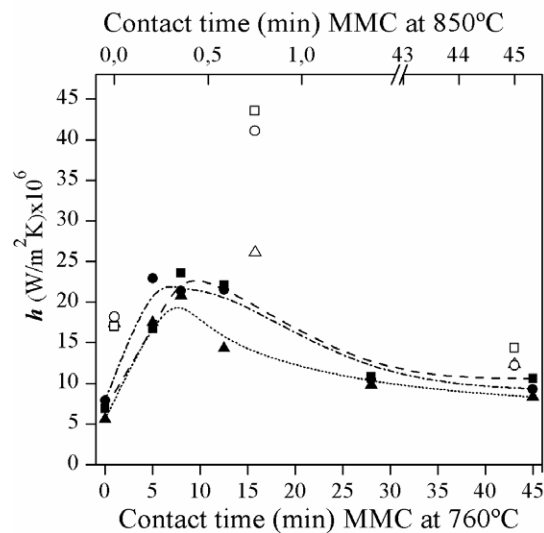


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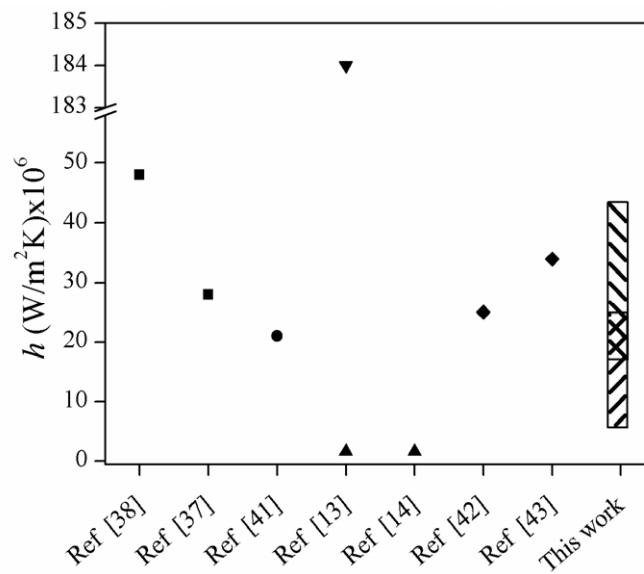


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