Heat-Conductive Adhesives – Cool Solutions for Versatile Applications

Electronic devices are becoming ever smaller and more powerful, which increases the heat their components generate and that needs to be dissipated. This increased thermal load reduces the components' performance and shortens their service life. An optimized heat management helps protect the devices and increase their performance.

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Thermally conductive adhesives: flexible in application

Thermally conductive adhesives dissipate heat efficiently while providing electrical insulation – an important requirement in many applications, for example in computer technology or in the production of today's high-performance batteries for electric vehicles. Their use also ensures a permanent positive connection of the components. In contrast to other heat-conducting materials, no mechanical fasteners, such as screws or clamps are needed. The choice of the right adhesive is vital here to take advantage of the exceptional versatility of this technology: The adhesives must allow precise dosing and provide good surface wetting with positive gap bridging to compensate for uneven joint surfaces. These characteristics ensure a high adhesive strength also between different materials, such as metals, ceramics and plastics (*Figure 1*). Thanks to their high level of adaptability, adhesives can be optimised for each application, allowing components of different shapes and sizes to be bonded in a single step with the same adhesive: Heat sinks, for example, can be permanently bonded to the cooled component without the need for additional mechanical fixing. All this makes bonding by far the most universal joining method. It offers designers a high level of freedom and can be easily integrated into most industrial manufacturing processes in both one-off and mass production.

Epoxy adhesives – versatile and reliable

For many applications, solvent-free reaction adhesives or chemically curing systems are particularly suitable. These adhesives consist of low-molecular and thus

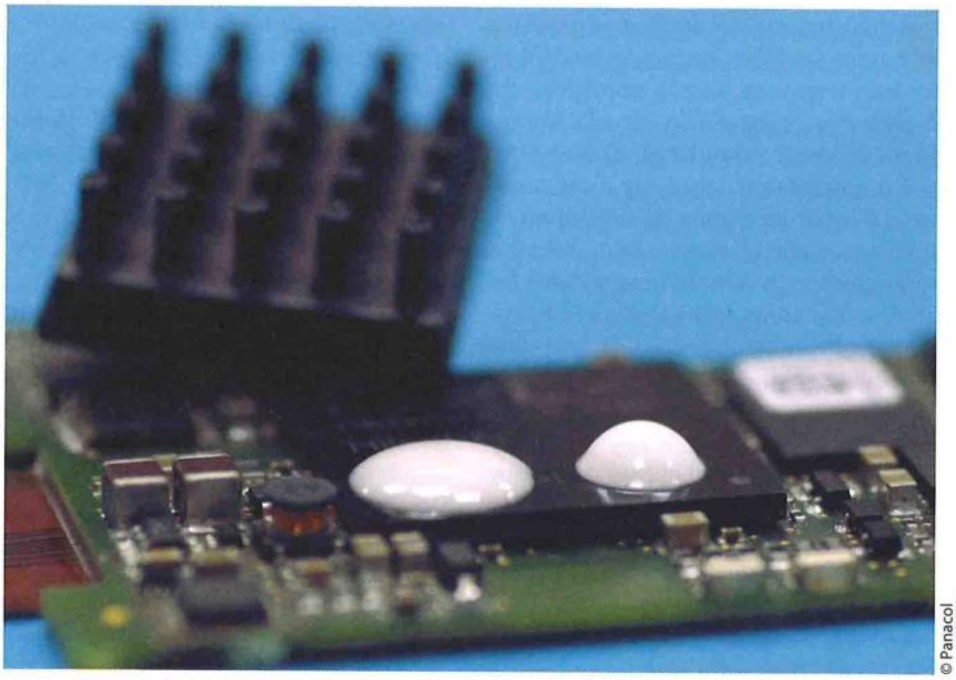
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Figure 1 > Application of two adhesives with different flow behaviours – the different wetting behaviours and dimensional stability are clearly visible.

low-viscosity substances that can react with each other under defined conditions and ultimately form polymeric substances of high molecular mass and thus high mechanical resistance /1/. Epoxy-based adhesives are particularly suitable for this purpose. These resins' name is derived from the epoxy function, in which an oxygen atom forms a tripartite ethylene oxide (oxirane) ring with two carbon atoms. This triple ring also explains the high reactivity of the epoxy group /2/, which allows systems with different curing mechanisms (thermal, UV, 2C) to be realised. While single-component thermal or UV-curing systems cure relatively quickly under precisely defined conditions, the curing speed (i.e. a short or long pot life) of 2C systems must be set by selecting a suitable resin/hardener combination.

Epoxy adhesives exhibit excellent adhesion to a wide variety of substrates, good temperature resistance and a high resistance to chemicals and solvents. Due to their high cross-linking density, adhesive layers of epoxy resin base materials have high long-term static resistance to creep loads. If the adhesive layer is later exposed to deformation through dynamic load, specially adjusted epoxy adhesives allow a stress reduction without damaging the bond. Provided they are expertly designed, there is no need to doubt the long-term durability of bonded joints.

Filler	Description	Thermal conductivity* [W/mK]	Particle shape	€/kg
Al_2O_3 type I	Aluminium oxide, standard type	30	Irregular	
Al_2O_3 type II	Aluminium oxide, special grain shape	30	Round	
AlN type I	Aluminium nitride, standard type	180	Irregular	
AlN type II	Aluminium nitride, special grain shape	180	Round	
BN type I	Hexagonal boron nitride, optimised particle size distribution	330	Platelet-shaped	
BN type II	Hexagonal boron nitride, high specific surface area	330	Platelet-shaped	

Table 1 > Selection of thermally conductive fillers

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Fillers – only the right filling brings the right cooling

Epoxy adhesives (polymers) as such have a low thermal conductivity (approx. 0.2 W/mK). This can be increased by several W/mK merely by adding special fillers. These are usually ceramic particles which, depending on their type and

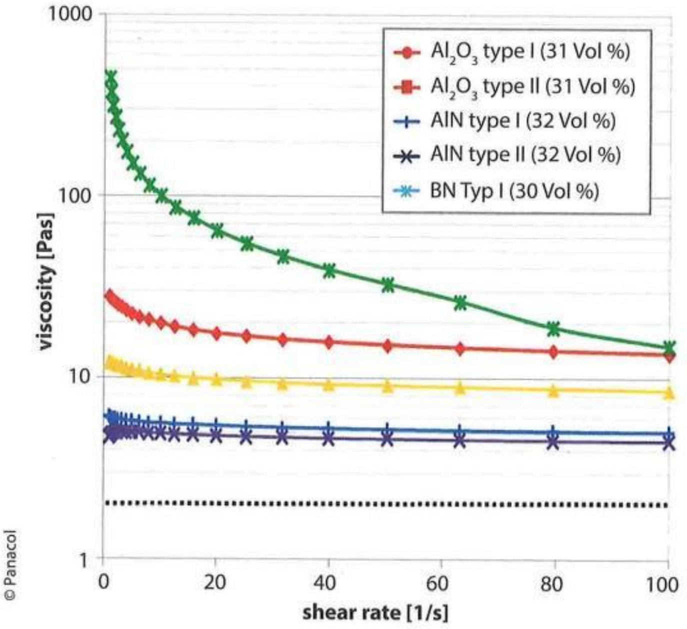

Figure 2 > Influence of different filler types on the flow behaviour with comparable filling degree (% volume); the viscosity of the base resin without filler is 2 Pa·s (black dashed line).

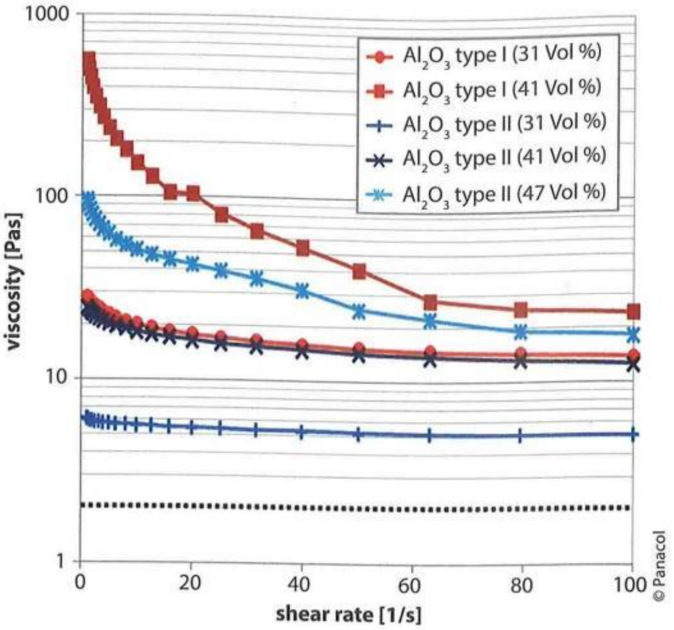

Figure 3 > Comparison of the influence of particle shape on viscosity; a higher filling degree can be achieved with round particles (type II – blue) at lower viscosity than with irregularly shaped particles (type I – red).

chemical structure, can be irregular in shape, round or platelet-shaped and have a characteristic particle size distribution. *Table 1* lists commonly used fillers. Metallic fillers can also be used, although these have the drawback of being electrically conductive, which is not desired in many applications. Ideally, thermally conductive fillers should have a high thermal conductivity, low thermal expansion, low abrasiveness and good chemical resistance.

Development of thermally conductive adhesives

The development of thermally conductive adhesives focuses mainly on how different fillers affect the adhesive's thermal conductivity. In addition to filling degree, size and distribution of the particles, the type of material used and its particle shape significantly influence the adhesive's properties. The filler material also affects its flow behaviour – an important point to bear in mind as the right viscosity is important in later application: While too low a viscosity can impair edge stability or causes the adhesive to run, an excessive viscosity often leads to incorrect application of the material, for example because a rough surface is not fully wetted to yield a positive fit. Too high a viscosity can also cause problems in dosing.

Model systems

To investigate the differences between the various thermally conductive fillers, a 2C epoxy model system was selected. First, a uniform filling degree of about 30 % by volume was chosen for the different fillers (*Table 1*). To investigate the effect of different particle geometries, two different variants of aluminium oxide (Al_2O_3 types I and II) were chosen: Al_2O_3 with random particle shape, and a type with spherical particles. The grain size in both cases is about 10 µm.

To produce the model adhesives, the appropriate filler was added to the epoxy resin (Epikote 320), blended in a SpeedMixer and degassed. The same procedure was followed with the curing agent (Ancamine 2432). To produce the specimens for thermal conductivity testing, both components were mixed under vacuum.

The thermal conductivity was determined by laser flash analysis: A defined amount of heat was introduced into the sample by means of a laser pulse and the temperature rise on the sample's top surface was measured. From this reading, the thermal conductivity was determined. The flow properties were measured with the Kinexus lab+ rheometer from Malvern. The viscosity of each sample was measured at different shear rates. All measurements were taken at 25 °C.

Flow behaviour of thermally conductive adhesives

Viscosity values are not constants: they are influenced by many conditions. This applies in particular to adhesives, as these, being polymer-based, tend to form an internal structure. This effect is further enhanced by the addition of fillers. Under shear stress, the particles align in the direction of flow to a certain extent and therefore glide past each other more and more easily. Filled adhesives therefore exhibit shear-thinning behaviour, i.e. their viscosity decreases with an increase in applied shear rate /3/.

A detailed examination of the flow behaviour is useful, as information about the uncured adhesive can be obtained in the low-shear range, i.e. when a low force is exerted on the material. This shows, for example, whether the adhesive bead runs after application or retains its shape. In the high-shear range, processes involving higher forces can be simulated. This allows the extent to which the applied adhesive runs out of the gap during joining of components to be determined, or whether correct dispensing is possible at all.

Figure 2 shows the influence of different filler types at comparable filling degree (approx. 30 % by volume). It can be seen that the resulting viscosity depends less on the chemical nature of the filler than on its particle shape and size. While fillers with spherical particles (Al_2O_3 type II and AlN type II) result a rather low viscosity, irregularly shaped particles (Al_2O_3 type I and AlN type I) result in a much higher viscosity. The platelet-shaped boron nitrides lead to such a significant increase in viscosity that a pasty (BN type I) or even a kneadable (BN type II – not measurable) mass is obtained. *Figure 3* illustrates this: With the round Al_2O_3 (type II), significantly higher filling degrees can be achieved at low viscosity than with an irregular grain shape. The particles can glide past each other more easily without getting stuck. For correctly adjusted flow properties, the choice of filler is therefore crucial.

Thermal conductivity

Thermal conductivity is generally defined as the amount of heat that passes through a body of a defined cross-section within a defined unit of time. Non-metallic solids (such as cured adhesives and ceramic fillers) do not normally contain mobile electrons. They cannot, therefore, transport heat through convection or conduction electrons; heat transfer can take place only by an energy exchange through lattice vibrations (phonons).

At a constant volume fraction of filler, an adhesive's thermal conductivity increases with the thermal conductivity of the filler material (*Figure 4*). The dashed line shows the increase in thermal conductivity of the model adhesive as a function of the intrinsic thermal conductivity of the filler (Al_2O_3 < AlN < BN). However, the significant differences in the fillers' thermal conductivity does not have a correspondingly proportional effect on the thermal conductivity of the adhesive. One explanation for this behaviour lies in the different shapes of the filler particles. As a general rule, the greater the number of contacts between the individual particles, the higher is the conductivity. Depending on the shape and size of the filler particles, there is more epoxy polymer between the particles at the same volume fraction, thus forming an insulating separating layer that hinders heat transport.

It follows that the thermal conductivity of the adhesive increases with increasing filler content (*Figure 5*). But here, too, there is a strong dependence on particle shape. For example, irregularly shaped Al_2O_3 particles (type I – red symbols) tend to have a slightly higher thermal conductivity than round particles (type II – blue symbols). Round Al_2O_3, on the other hand, allows a much higher filling degree and ultimately a higher conductivity to be achieved as well as yielding a good processing viscosity (cf. *Figure 3*).

When using thermally conductive adhesives, it is important to ensure that the fillers are distributed as densely and homogeneously as possible within the adhesive. This is the only way to avoid cavities in the cured adhesive layer, which would lead to a reduction in thermal conductivity. Beside careful production by the manufacturer, it is important to ensure correct application by the user, for example to avoid the inadvertent introduction of air during the dosing process. Attention must also be paid to possible sedimentation during storage.

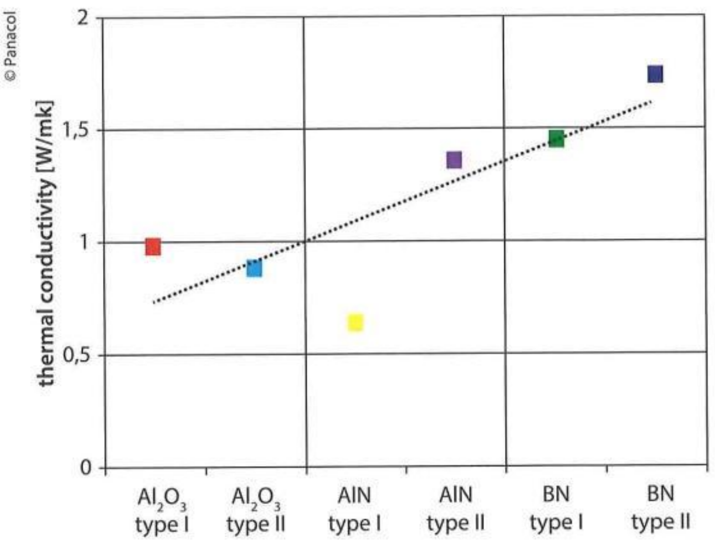

Figure 4 > Resulting thermal conductivity when using different fillers. The filling level in all cases is approx. 30 % by volume; the dashed line illustrates the trend.

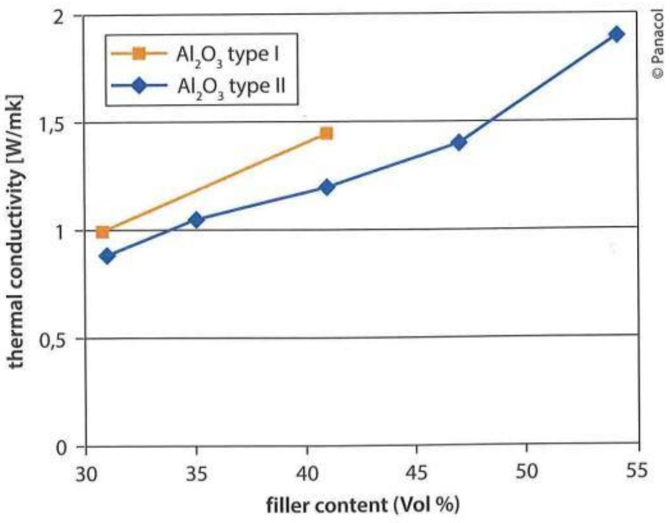

Figure 5 > Thermal conductivity with increasing filling degree of Al_2O_3. With Al_2O_3 type I (red), a higher thermal conductivity can generally be achieved than with type II (blue). However, type II tends to achieve higher filling degrees and ultimately a higher absolute thermal conductivity.

Criteria to be considered when developing adhesives	Advantages of thermally conductive adhesives
Required thermal conductivity	Large selection of different fillers (types, particle shapes and particle sizes) available
Mechanical requirements on the cured adhesive	Large formulation variance allows precise adjustment of the flow behaviour and properties of the cured adhesive
Curing mechanism (thermal / UV / 2C)	Positive-fit application
Bonding layer thickness	Components of different dimensions can be bonded with the same adhesive
Processability / application	Permanent mechanical fixing of the components
Flow properties	High resistance of cured adhesive
Storage stability	High dielectric strengths possible
Costs / economic efficiency	

Table 2 > The greatest strength of thermally conductive adhesives results from their versatile properties.

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Summary

Choosing the right filler is anything but trivial. Boron nitrides, for example, provide high thermal conductivity but usually cause unfavourable flow properties. They are also expensive. In addition, ceramic fillers have the disadvantage of being highly abrasive due to their hardness. This problem can, however, be alleviated by selecting a suitable particle shape.

As a general rule, in addition to the filling degree, properties such as the shape and size of the particles play an important role. By carefully selecting the appropriate filler, the flow properties, thermal conductivity and properties of the cured adhesive can be specifically optimised. When developing an adhesive, it is generally important to match both the fillers and the adhesive formulation to previously determined application-specific criteria (*Table 2*). This also allows, for example, a high dielectric strength of over 25 kV/mm to be achieved – an important property in the insulation of live parts in industrial electronics production.

The adhesive developer, then, has a variety of possibilities for precisely adapting the properties of the thermally conductive epoxy adhesive to its specific application. *Table 2* summarises the main advantages of thermally conductive adhesives over other heat-conducting materials. Modern thermally conductive adhesives are thus able to perform a diverse range of demanding functions, which will further expand their areas of application in the future. //

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