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FP7 Project Thermaco: Metal Matrix Composites with carbon based inserts obtained by casting processes

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This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement No 608978.

FP7 Project "THERMACO": High conductive Aluminium Metal Matrix Composites with carbon based inserts obtained by casting processes

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This lecture aims to present the EU-FP7 project "THERMACO" which focuses on the production of new high conductive carbon based MMC (Metal Matrix Composites) obtained by casting processes. These novel, extremely efficient, thermally conductive materials are particularly targeted to heat evacuation applications in critical fields such as power micro-electronics, e-mobility and (renewable) energy generation as well as highest performance combustion engines.

Some preliminary numerical results obtained by project activities are here presented. The investigated composite material is a commercial aluminium alloy (A356) reinforced with different carbon based materials that have been selected and employed as inserts to enhance the thermal conductivity of the matrix. The thermal behaviour of the obtained materials has been studied by means of theoretical (EMA - Effective Medium Approximation) and numerical (FEM - Finite Element Methods) approaches in order to determine the effective thermal conductivity in the different directions of heat dissipation.

The effects of thermal resistance at the interfaces between matrix and inserts have been considered in order to numerically evaluate influence of casting process parameters which determines the quality of interfaces between the different materials of composites.

The numerical results have been validated by direct thermal conductivity measurements on sample of the obtained materials by means of a thermofluximeter instrument (NanoFlash Light Flash System).

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What does THERMACO do – The Problem-Opportunity-Solution Scenario

- Many KETs depend on efficient heat evacuation; example:
  - Processors, Transistors,… are destroyed when too hot, but generate massive heat themselves

Current Technological Limit

- Further integration/downscaling on chip level not possible
- Need for large/directly connected cooling systems limits design freedom/downscaling on application/part level

- New material shows extremely positive conductivity values:
  - Graphene being discovered only in 2004

Novel Opportunity

- Up to 4000W/m*K (10x Cu) thermal conductivity in-plane
- Very low conductivity cross-plane

⇨ **Apply to production/process chain/part**

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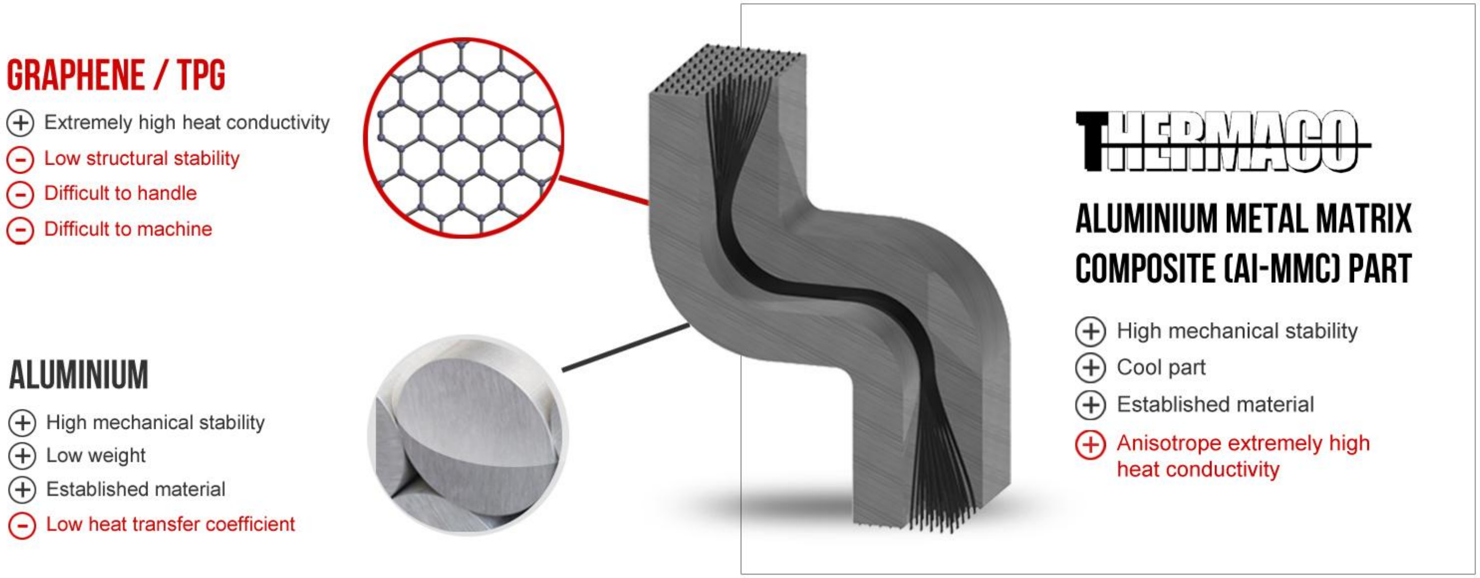
Smart Thermal Conductive Al-MMCs by Casting

THERMACO aims at providing manufacturing technologies for extremely efficient solutions in heat evacuation based on Aluminium Metal Matrix Composites (Al-MMC) with Carbon-based thermal highway inserts.



We generate design guidelines and reliable and efficient manufacturing technologies for novel composite parts using insert production, casting simulation, investment and gravity die casting, surface micro structuring, precision machining and LCA.

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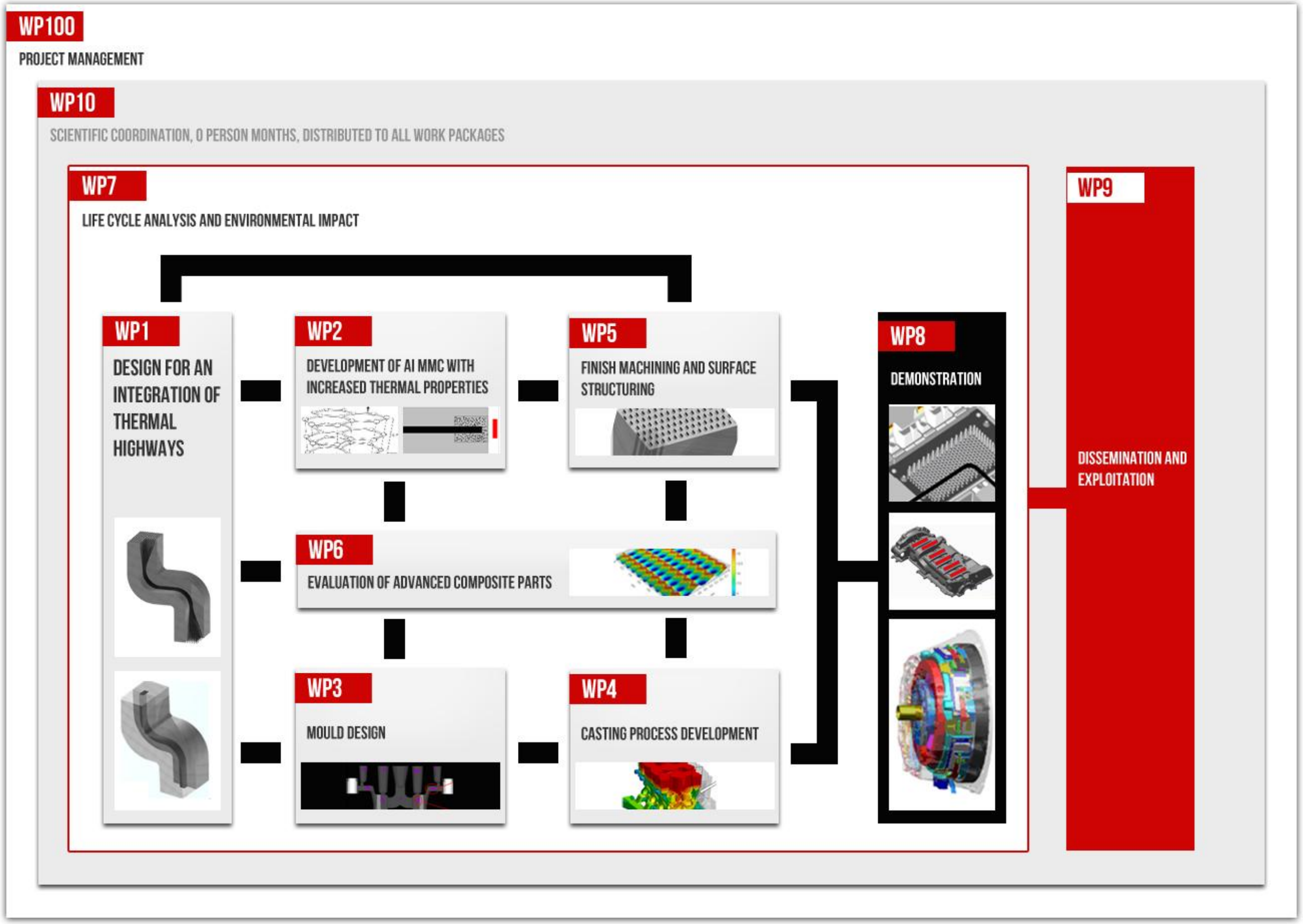
Holistic Industrial/Application Ready Project

Target groups
- (power) electronics
- Automotive / e-mobility
- Machine tool industry
- Aerospace
- Medical devices

Expected impact
- Enhance cooling efficiency dramatically
- Increase functional integration possibilities
- Allow for completely new component designs and manufacturing routes
- Enhance utilisation of composite materials
- Reduce cost and waste
- Bolster competitiveness and market strength through innovation and industrial leadership



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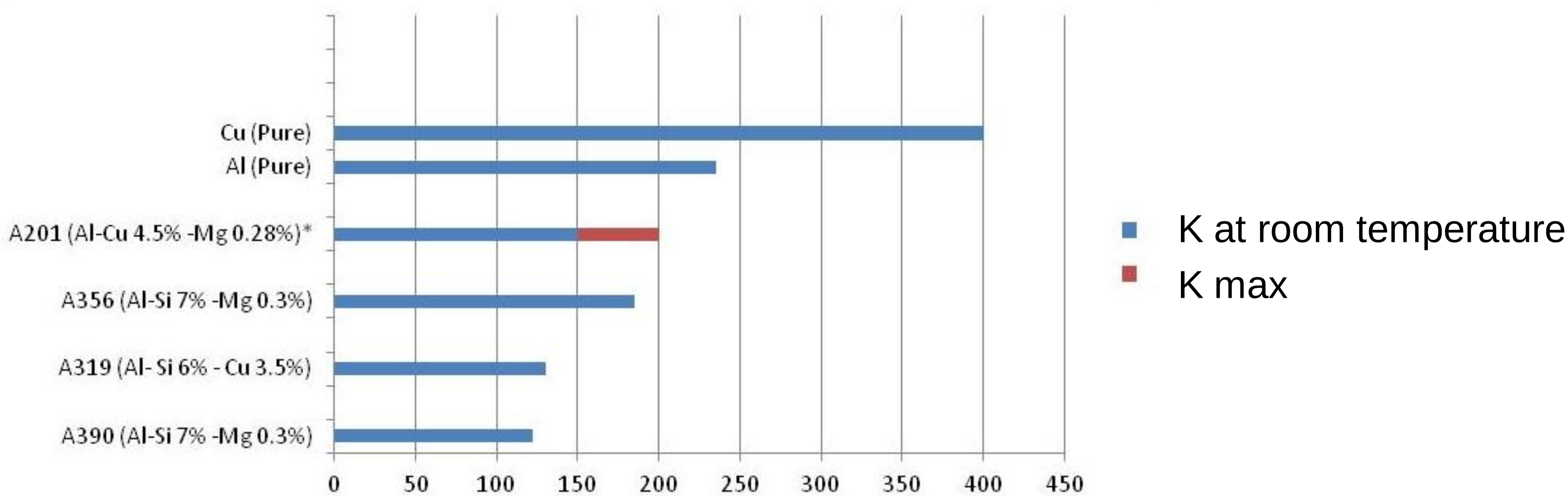
Solutions for improvement of thermal conductivity in aluminium composites

Linear Improvement (K* ∝ Km)

Possible change of Al alloys for matrix material:

(Some Al alloys have better thermal conductivity at high temperatures)

* Data from Procast database



Thermal Conductivity Km [W/mK]

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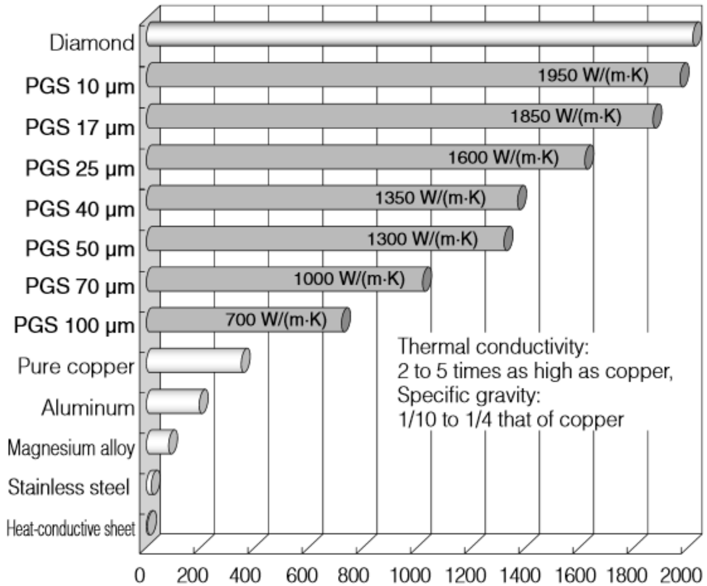
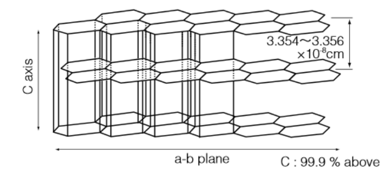
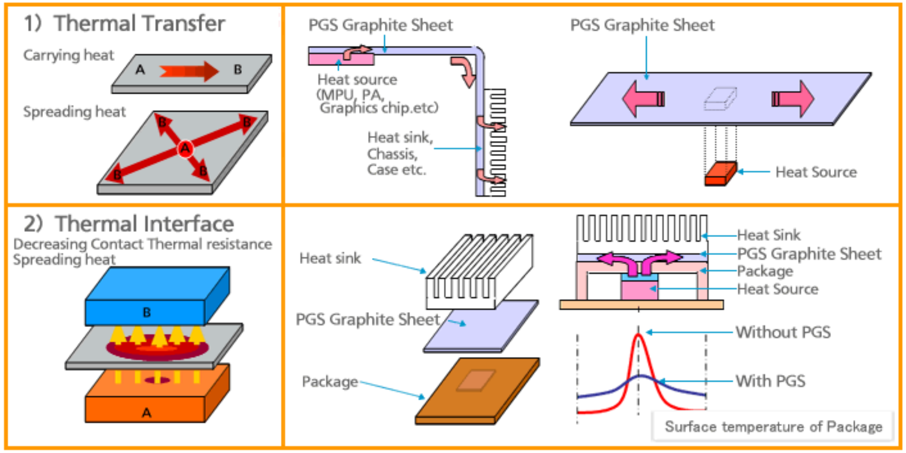
Carbon based solutions used as encapsulated inserts

■ Comparison of thermal conductivity (a-b plane)







http://industrial.panasonic.com/ww/i_e/00000/led_solution_e/led_solution_e/pgs_e.html

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Carbon based solutions as encapsulated material

Synthesis of Highly Conductive TPG*

Turbostratic PG
"as deposited"

Limited conductivity

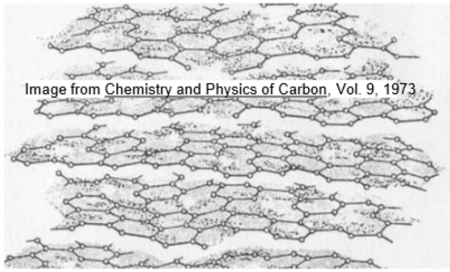

Image from Chemistry and Physics of Carbon, Vol. 9, 1973

- Formed from methane via CVD
- Classic 2-D, hexagonally ordered crystal structure
- 3rd dimension is DISORDERED
- Density 2.2 gm/cc
- Thermal conductivity 200-400 W/m-K

PG subject to heat treatment

Oriented TPG Graphite
"heat treated"

High conductivity

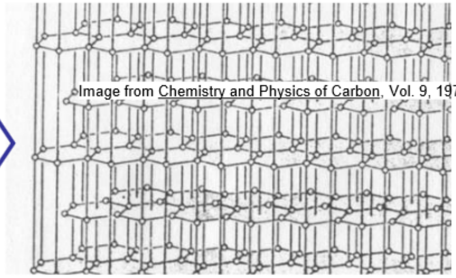

Image from Chemistry and Physics of Carbon, Vol. 9, 1973

- Additional ordering of 2-D structure
- ORDERED 3D crystal structure
- Phonon transfer (thermal conductivity) dramatically enhanced
- Lighter than Al - density 2.2 gm/cc
- Thermal conductivity >1500 W/m-K

High thermal conductivity on a-b plane

Very low thermal conductivity on c plane

MOMENTIVE performance materials

* TPG is trademark of Momentive Performance Materials, Inc.

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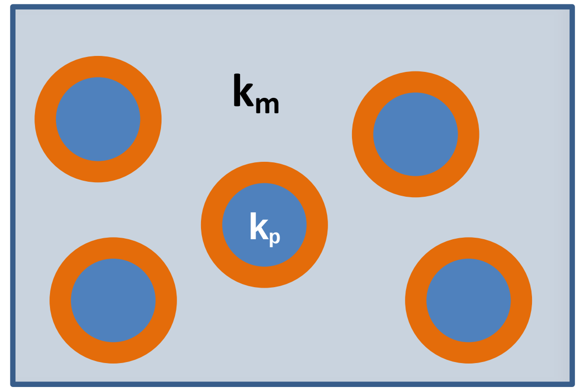
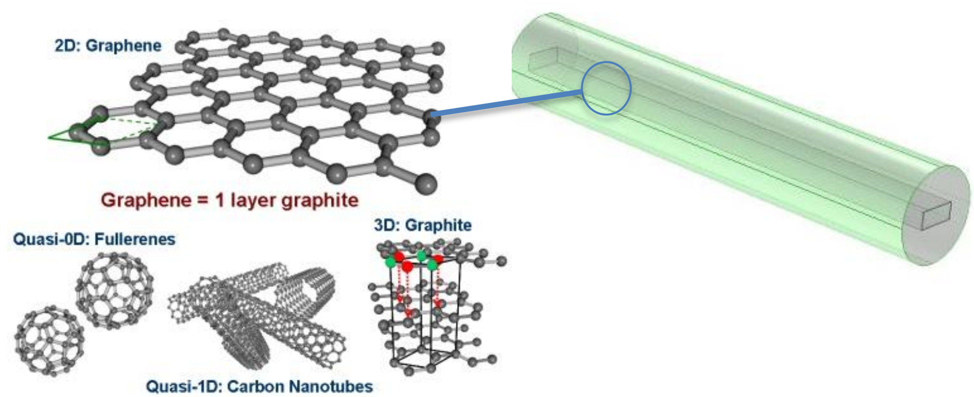
Casting ways able to produce MMCs with enhanced thermal conductivity

The potential strategies to join Carbon based materials with Aluminum are the following:

1. Disperding Carbon based particles (i.e. Diamond) inside Al-matrix:
    1. Solid route: metal powder pressuring and extruding
    2. Liquid route: desperding directly diamond powder in a liquid melt (high technical complexities)



2. Co-casting a liquid metal matrix around solid inserts (i.e. Pyrolytic Graphite)



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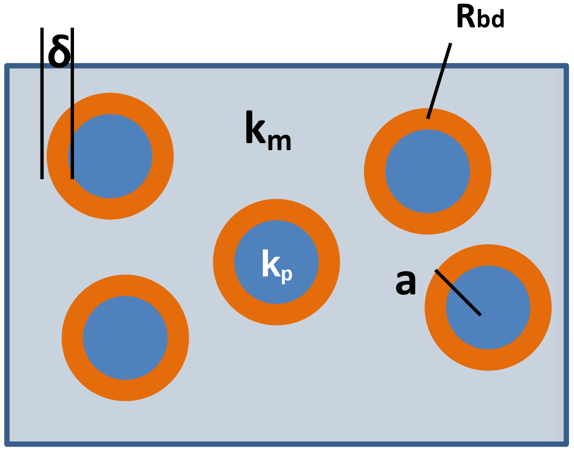
THERMACO

Analytical/numerical approach for Al composite embedding Gr/Diamond particles



Formulation for the limiting case of spherical particles

- k_p = particles thermal conductivity
- **a** = radius of particle
- f = volume fraction of particles.
- k_m = matrix thermal conductivity
- **δ** = Interface thickness
- **Rbd** = Interface Resistance between particles and matrix

The interfacial thermal property is concentrated on a surface of zero thickness and characterized by the **Kapitza radius** a_k

$$a_k = R_{Bd} K_m$$

were

$$R_{Bd} = \lim_{\substack{\delta \to 0 \\ K_s \to 0}} (\delta / K_s)$$

(k_s = thermal conductivity of interface)

Effective Thermal Conductivity of the Particle (considering the interface resistance)

$$K^p_{eff} = \frac{K_p}{1 + \frac{\alpha K_p}{K_m}}$$

Effective Thermal Conductivity of the Composite

$$K^* = K_m \frac{K_p(1+2\alpha) + 2K_m + 2f[K_p(1-\alpha) - K_m]}{K_p(1+2\alpha) + 2K_m - f[K_p(1-\alpha) - K_m]}$$

Were $\alpha = a_k / a$ dimensionless parameter

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Analytical/numerical approach for Al composite embedding Gr/Diamond particles

Effective Thermal Conductivity of the Composite

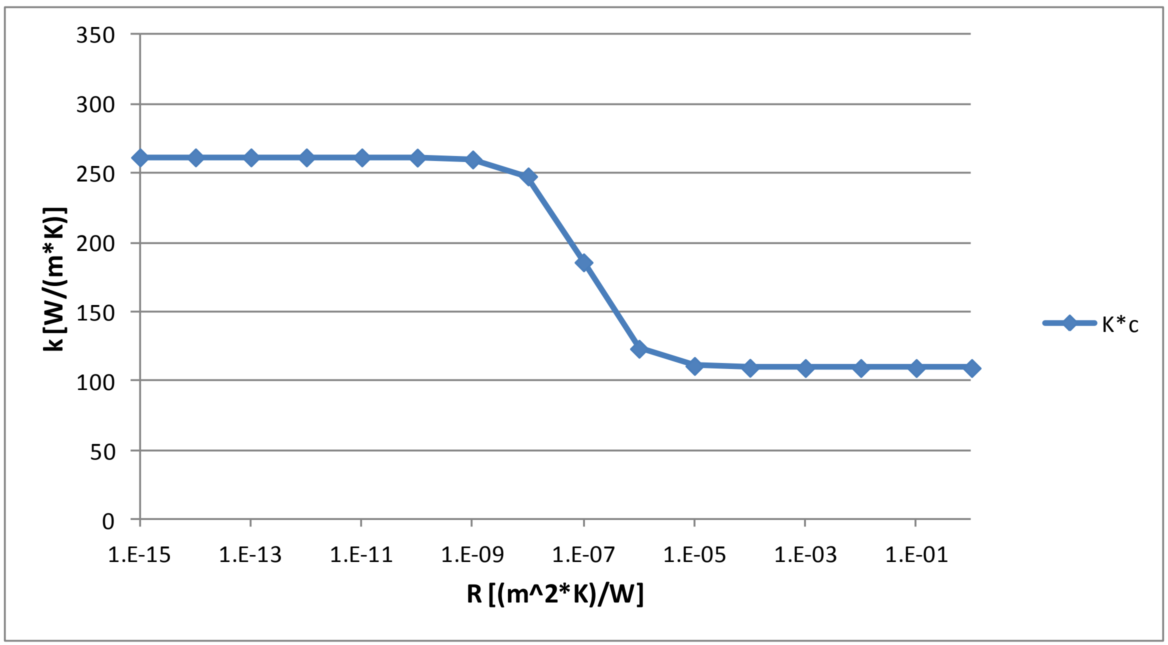
$$K^* = K_m \frac{K_p(1+2\alpha) + 2K_m + 2f[K_p(1-\alpha) - K_m]}{K_p(1+2\alpha) + 2K_m - f[K_p(1-\alpha) - K_m]}$$

$$a_k = R_{Bd} K_m$$

$$\alpha = a_k / a$$

Diamond input data

Kp =	600	[W/mK]
Km =	180	[W/mK]
a (radius)=	3E-05	m
f =	0.3	



The effect of the interface thermal resistance on the composite thermal conductivity can be observed. It has been discovered that this effect is always the same with the conductivity showing an asymptotic behaviour both for low and high thermal resistance with an inflection point in the middle, that is, behaving as a sigmoid curve.

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Analytical/numerical approach to predict Al composite embedding Gr/Diamond particles

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Composites Science and Technology
journal homepage: www.elsevier.com/locate/compscitech

Predicting the thermal conductivity of composite materials with imperfect interfaces

D. Marcos-Gómez [a,*], J. Ching-Lloyd [b], M.R. Elizalde [a], W.J. Clegg [b], J.M. Molina-Aldareguia [c]
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[b] Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, CB2 3QZ Cambridge, UK
[c] IMDEA-Materiales, c/Profesor Aranguren s/n, 28040 Madrid, Spain

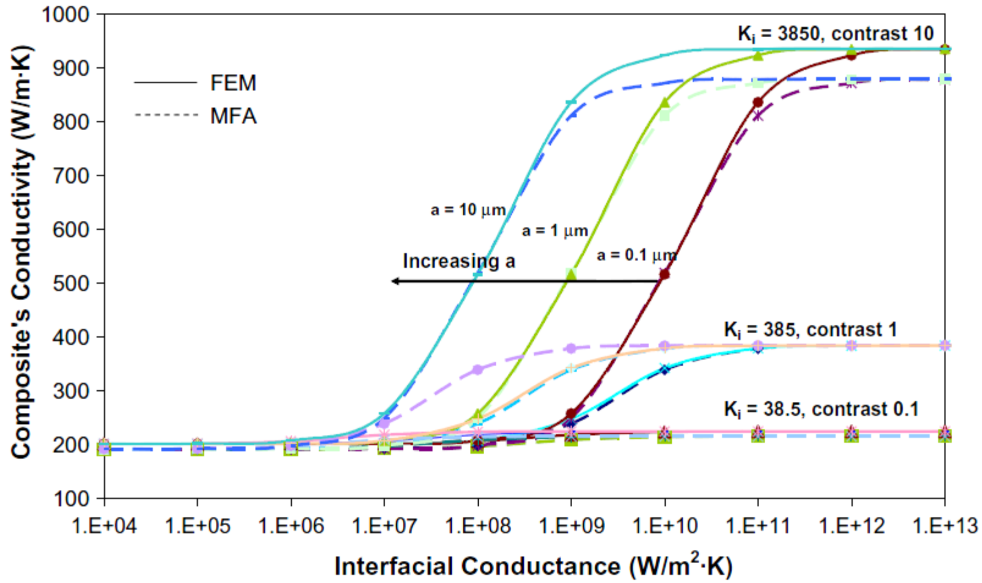

Fig. 6. Variation in composite conductivity with interface thermal conductance for a composite with $V_f = 0.4$, three different inclusion diameters (0.1, 1 and 10 µm) and three different phase contrasts (K_i = 38.5, 385, 3850 W m^{-1} K^{-1}).

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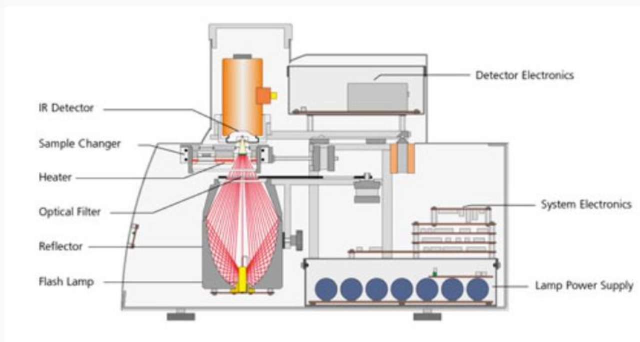
Direct measurements of thermal conductivity

LFA 447 NanoFlash®

NETZSCH

Determination of thermophysical properties is quick, easy and cost-effective with the new LFA 447 *NanoFlash*® Light Flash System.

A Xenon flash lamp takes the place of the laser, which is usually employed for this proven technique.



Schematic of LFA 447 NanoFlash®

LFA 447 *NanoFlash*® - Technical Specifications (subject to change)

Temperature range: RT to 300 °C
Xenon-Flash-Lamp 10 J/pulse, (adjustable power)
Contactless measurement of temperature rise with IR detector
Measuring range: 0.01 mm^2/s to 1000 mm^2/s (thermal diffusivity)
Measuring range: < 0.1 W/mK to 2000 W/mK (thermal conductivity)
Sample dimensions: 10 mm ... 25.4 mm diameter (also 8x8 mm and 10x10 mm, square) 0.1 mm to 6 mm thickness
Sample support for 4 samples
Sample holder: metal
Sample holder for liquids: aluminum / platinum
Atmospheres: air, static
MTX Scanning device for 50 mm x 50 mm samples (RT), local resolution 0.1 mm

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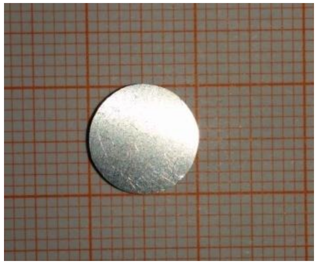
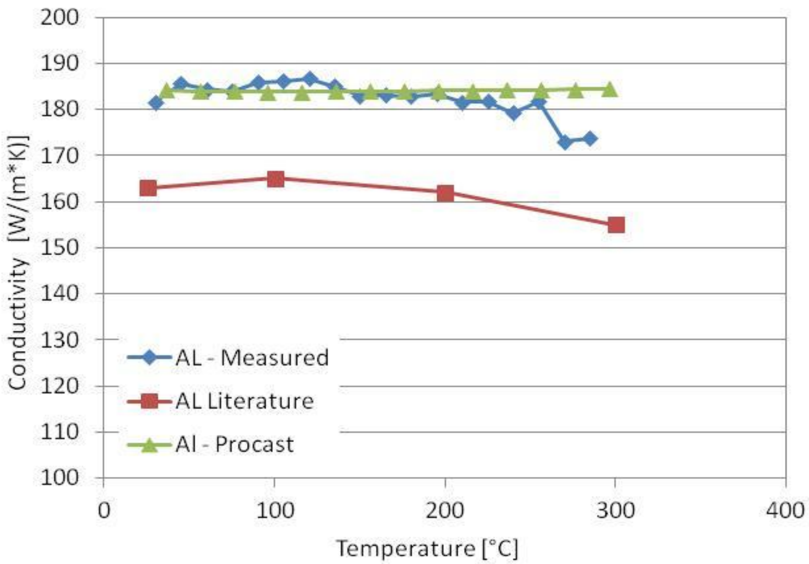
Direct measurements of thermal conductivity

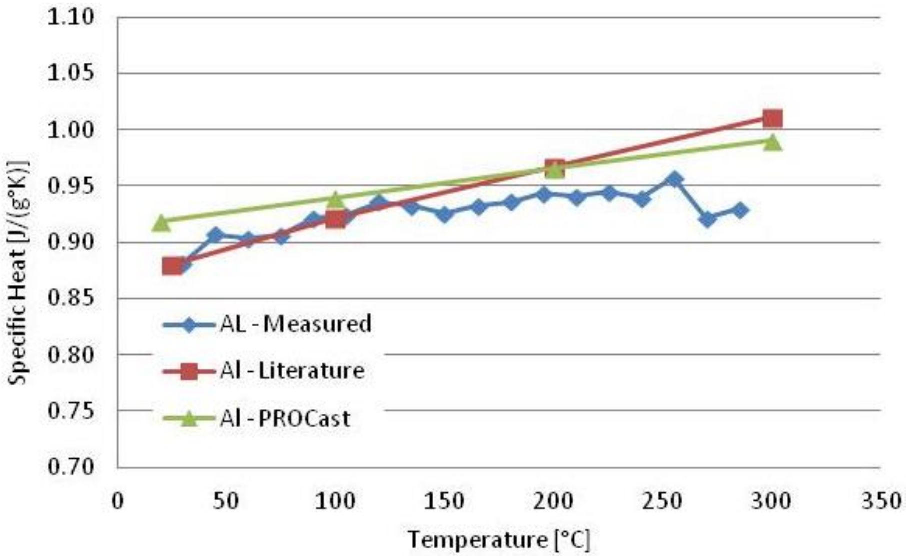
Aluminium Alloy (A356) - Matrix



Diameter: 10 mm

Tickness: 2 mm





K.C. Mills, *Recommended values of thermophysical properties for selected commercial alloys*, Woodhead Publishing Limited, 2002, Cambridge

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Direct measurements of thermal conductivity

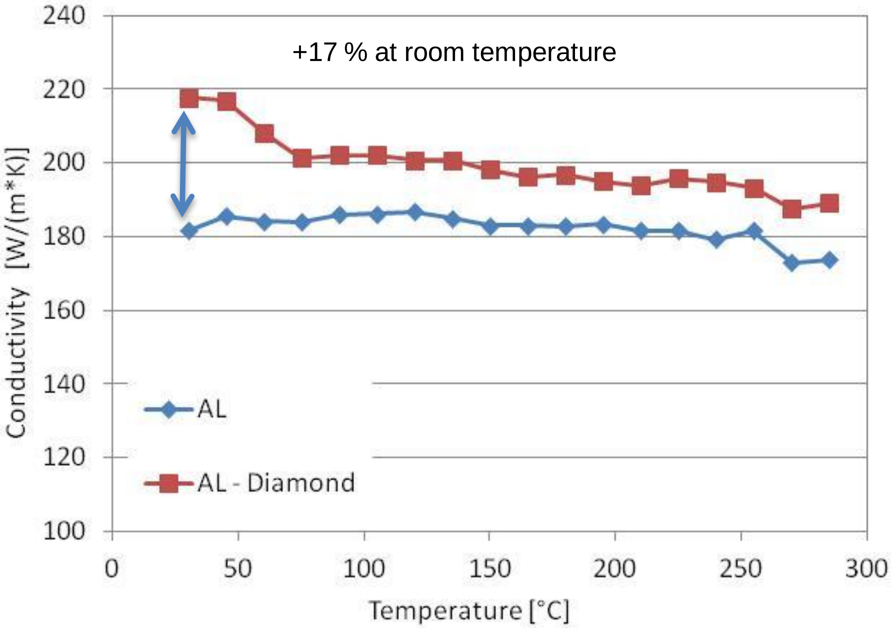
Al – Diamond particles

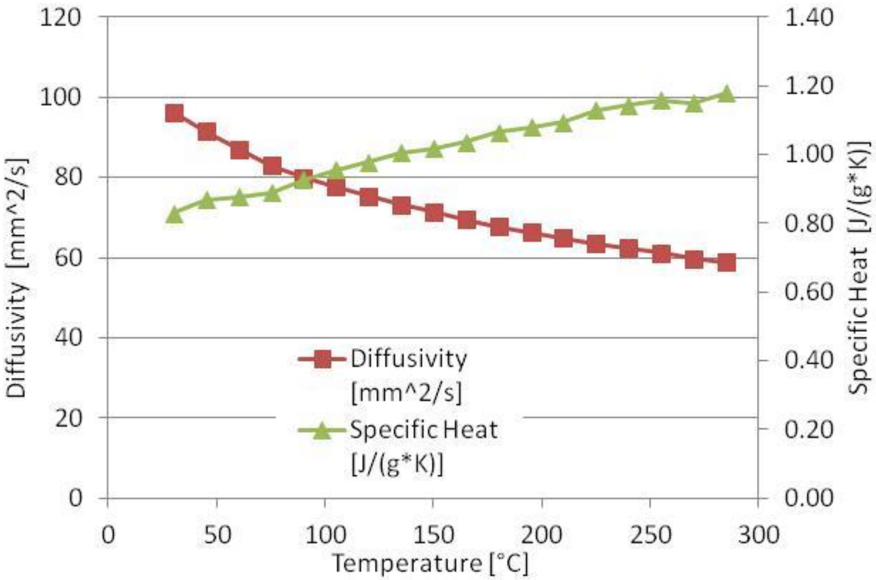
Particles radius = 30 µm

Vol. fraction = 30 %

Diameter: 10 mm

Tickness: 2 mm





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Direct measurements of thermal conductivity

Effective Thermal Conductivity of the Composite

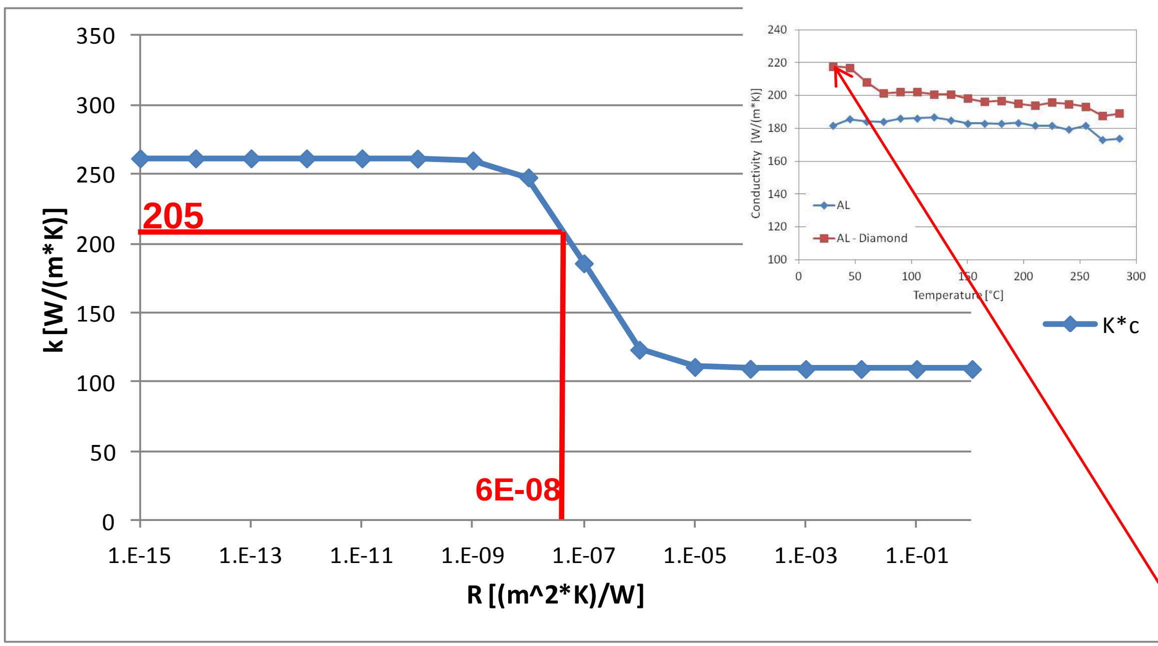
$$K^* = K_m \frac{K_p(1+2\alpha) + 2K_m + 2f[K_p(1-\alpha) - K_m]}{K_p(1+2\alpha) + 2K_m - f[K_p(1-\alpha) - K_m]}$$

$$a_k = R_{Bd} K_m$$

$$\alpha = a_k / a$$

Diamond data inputs

Kp =	600	[W/mK]
Km =	180	[W/mK]
a (radius)=	3E-05	m
f =	0.3	



Thermal Resistance (literature)*
Rbd = 6E-08 [m²/W°K]

Thermal Conductivity Calculated
K*c = 205 [W/m°K]

Thermal conductivity Measured
K*c = 217 [W/m°K] (30°C)

*C-Wen Nan, R. Birringer *Effective thermal conductivity of particulate composites with interfacial thermal resistance* J. Appl Phys. 97

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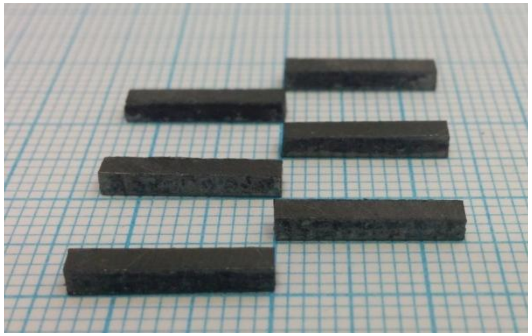
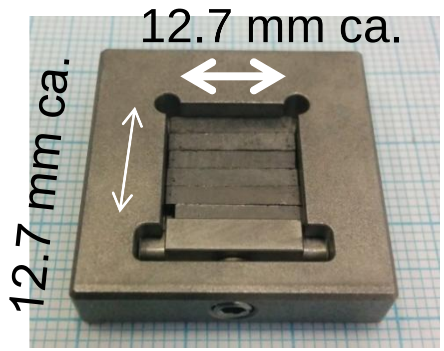
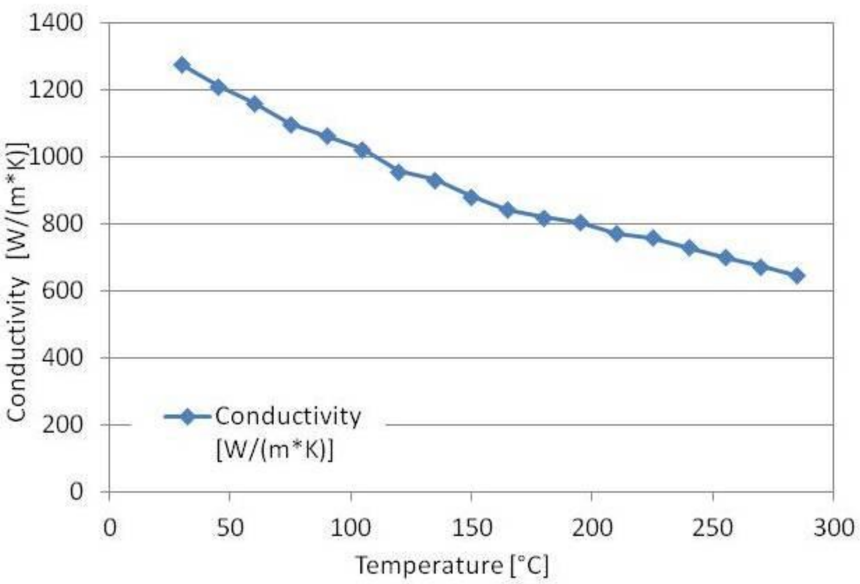
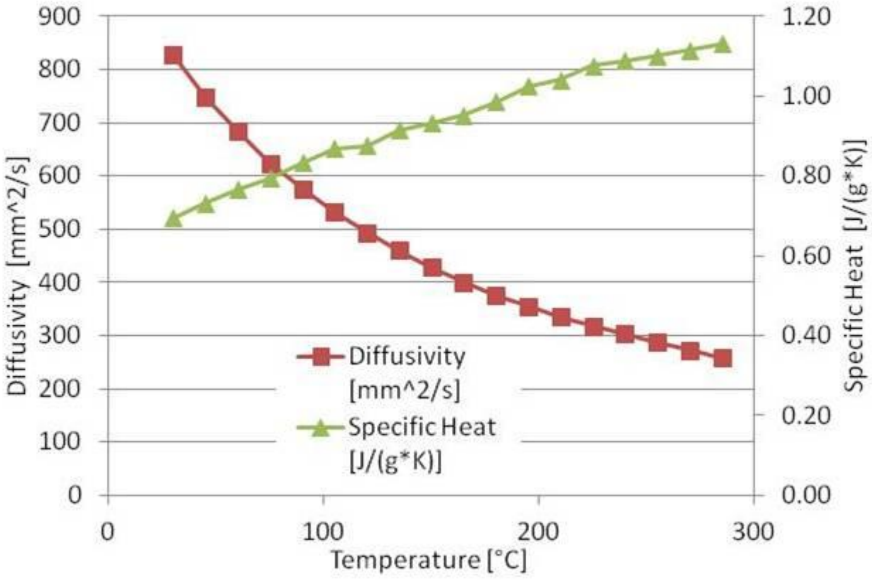
Direct measurements of thermal conductivity

TPG (k_{11} , k_{22})









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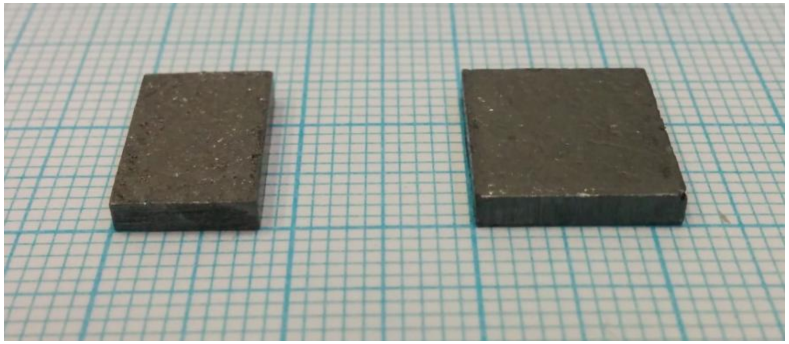
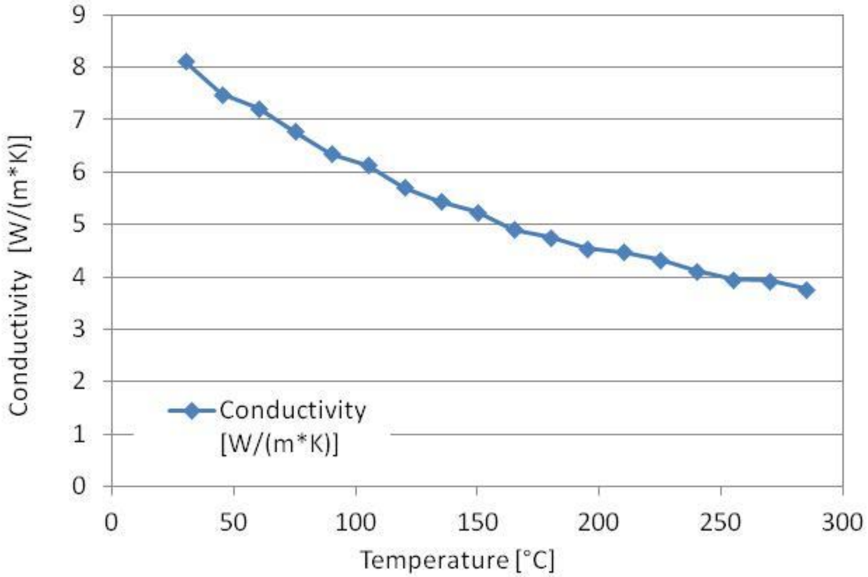
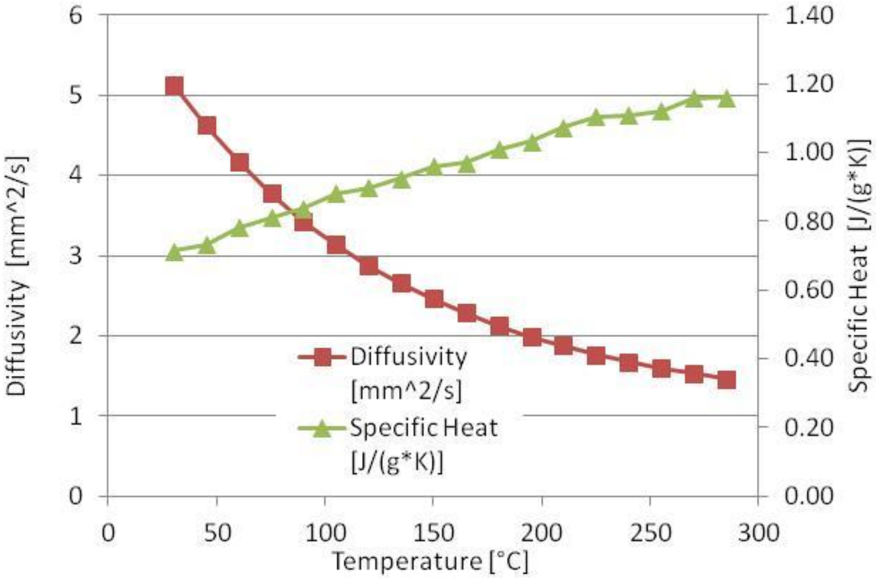
Direct measurements of thermal conductivity

TPG* (k_{33})







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FEM modeling of Al-TPG specimen experiment:

Conditions of experiment and Properties of materials

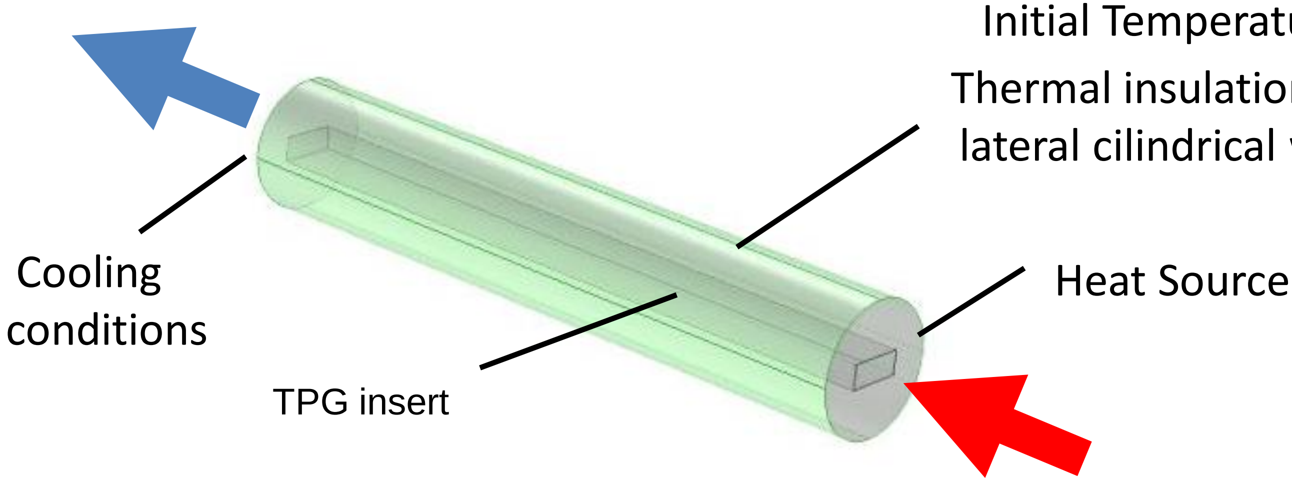
Materials Properties for :

- Graphite (TPG)
- Aluminium A356

Sample Total Lenght	**Ltot**	**60**	**[mm]**
Sample Diameter	**D**	**11**	**[mm]**
TPG Lenght	**Ltpg**	**60**	**[mm]**
TPG Height	**a**	**2**	**[mm]**
TPG Width	**b**	**4.5**	**[mm]**

Condition of experiment to set as Boundary Conditions

Initial Temperature of Sample



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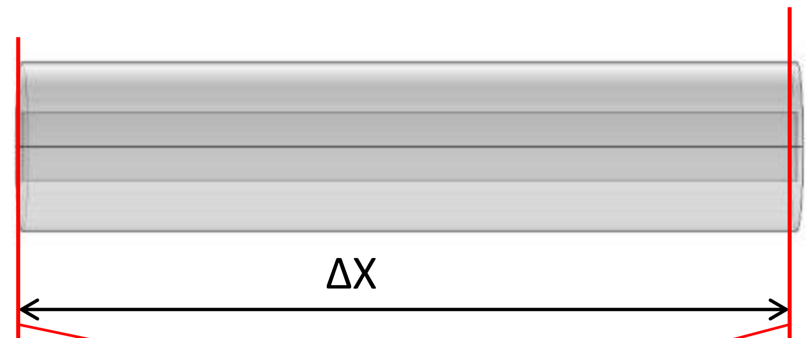
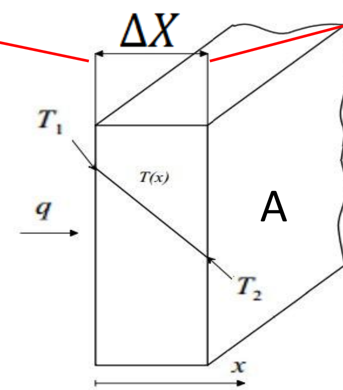
FEM modeling Al-TPG specimen:



The insulation on lateral walls allow to calculate the **effective conductivity** of the sample:

$$q_x^{avg} = -K_{1,1}^{eff} \frac{\Delta T}{\Delta X} \rightarrow K_{1,1}^{eff} = \frac{\int_A q_x dA}{A} \frac{\Delta X}{\Delta T} = K_{sim}$$



Data from Geometry :

- Distance between two different sections *[m]*
- Area of sample section A *[m2]*

Simulated Data :

- Average surface Temperature T *[°K]*
- Heat Q *[W]*

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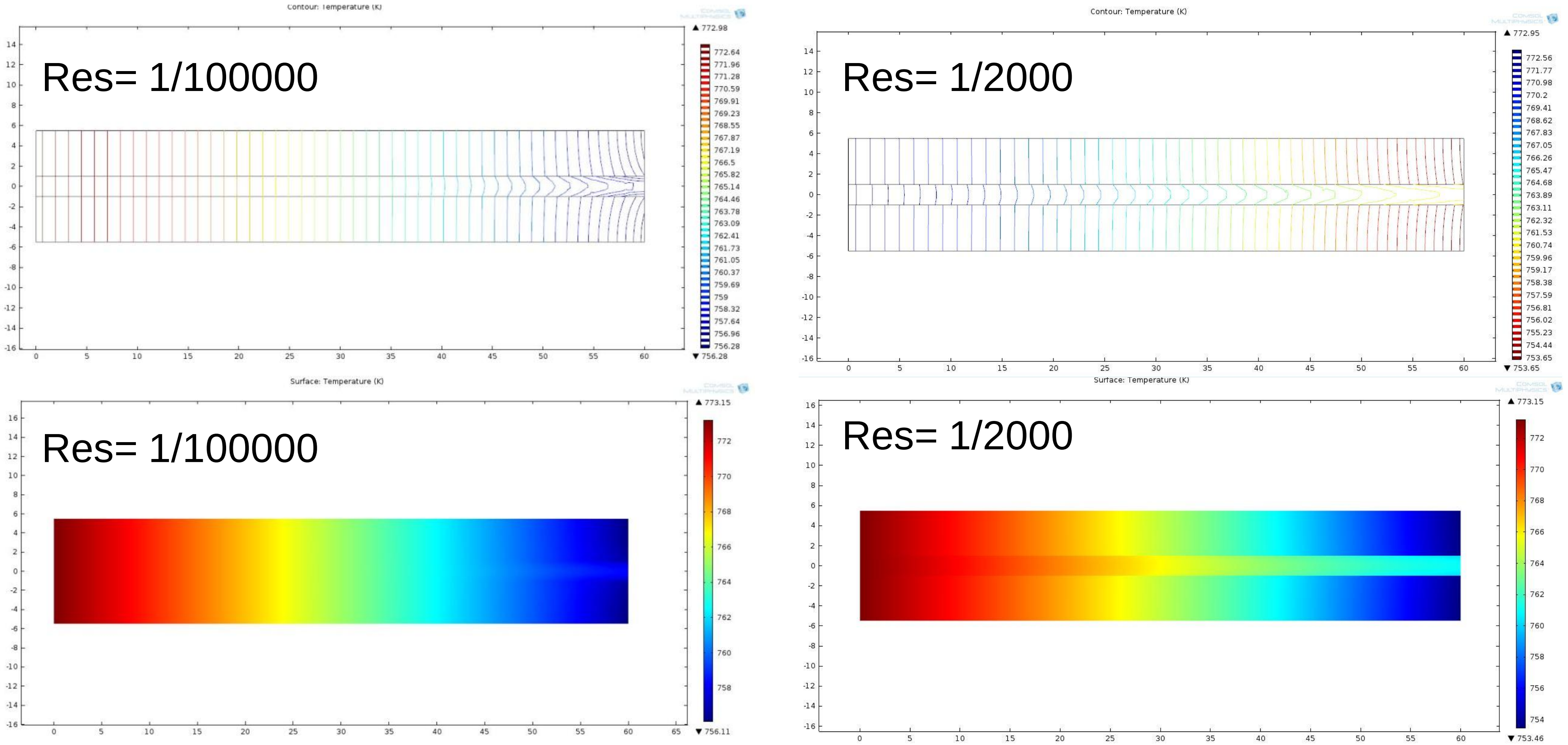
FEM modeling Al-TPG specimen:

Temperature distribution: effects of TPG/Al interface thermal resistance



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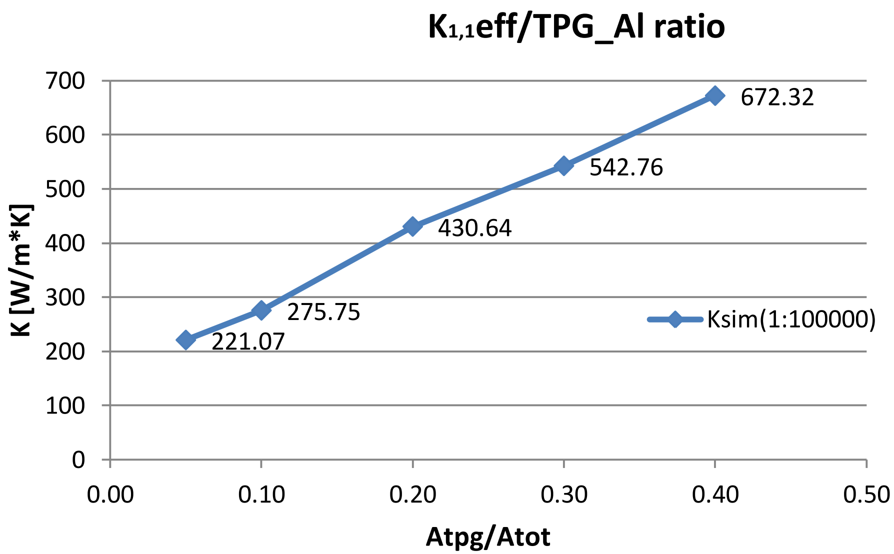
FEM modeling of Al-TPG sample:



Atpg/Atot	Ksim(R=1/100000)
0.05	221.07
0.10	275.75
0.20	430.64
0.30	542.76
0.40	672.32

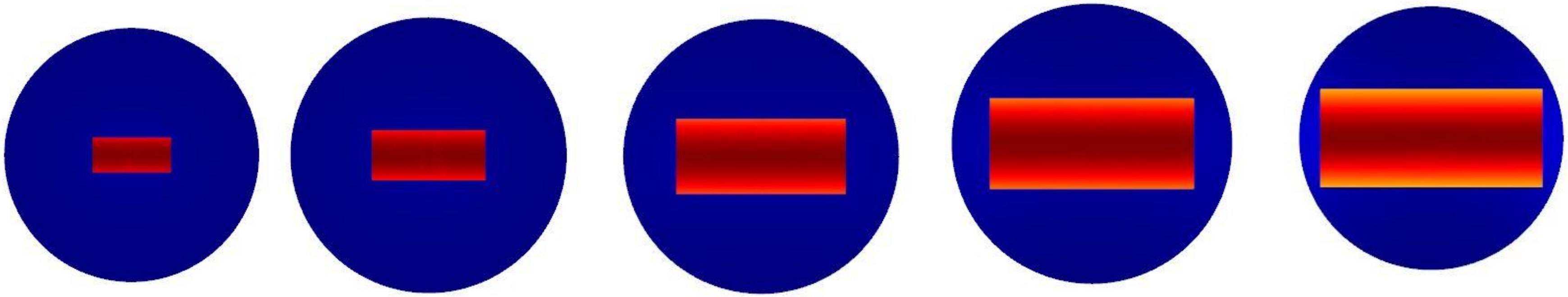
TPG Height	1.5	[mm]
TPG Width	3.375	[mm]

TPG Height	2	[mm]
TPG Width	4.5	[mm]

TPG Height	3	[mm]
TPG Width	6.75	[mm]

TPG Height	3.55	[mm]
TPG Width	7.99	[mm]

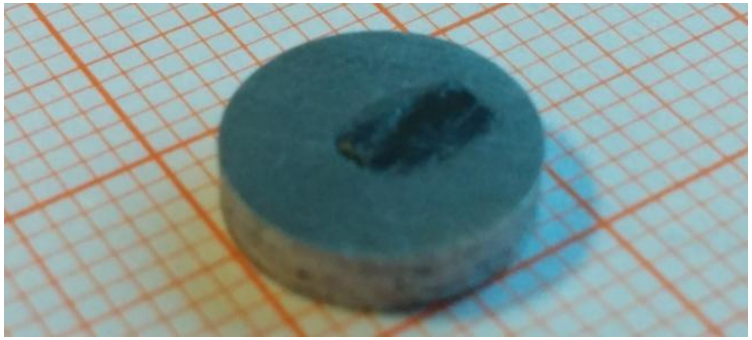
TPG Height	4.1	[mm]
TPG Width	9.23	[mm]

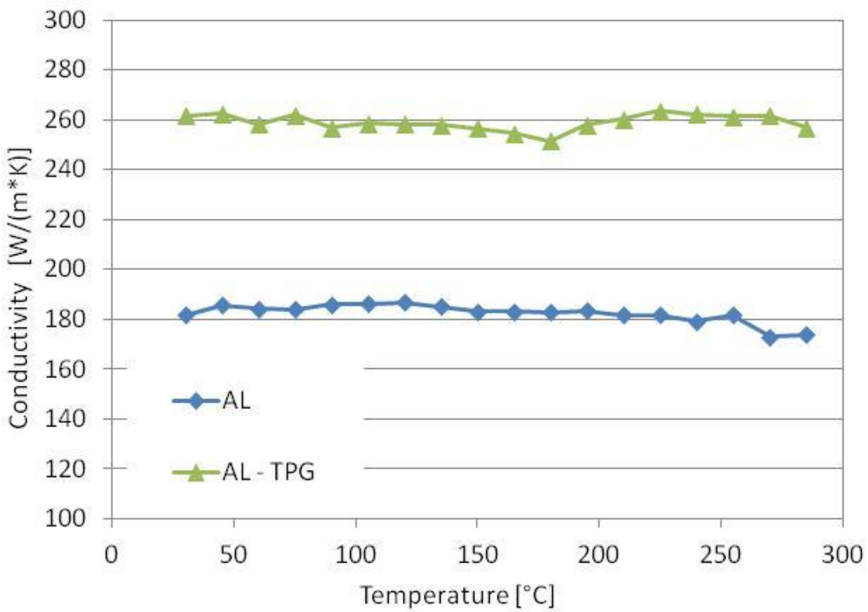


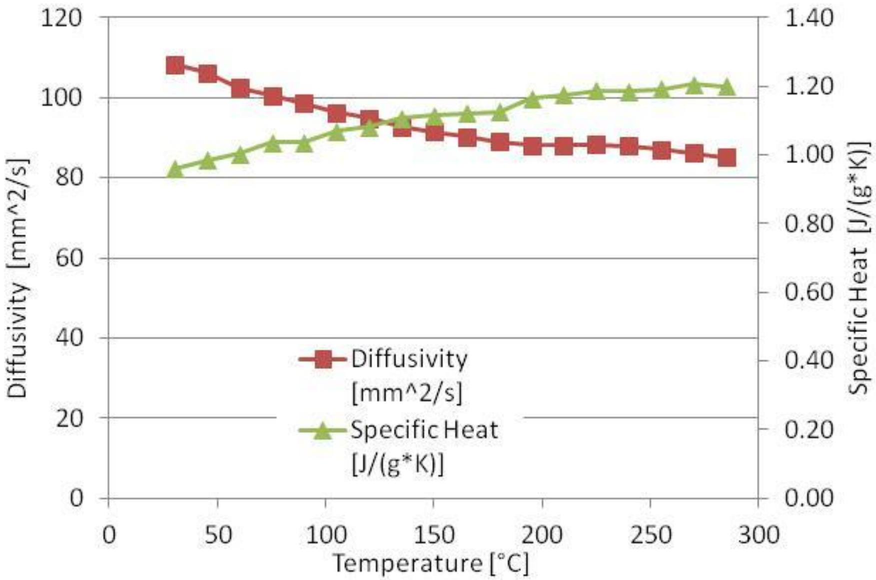
grant agreement No 608978.

Direct measurements of thermal conductivity with Nano-Flash Instrument

(Al – TPG) Ratio = 0.1







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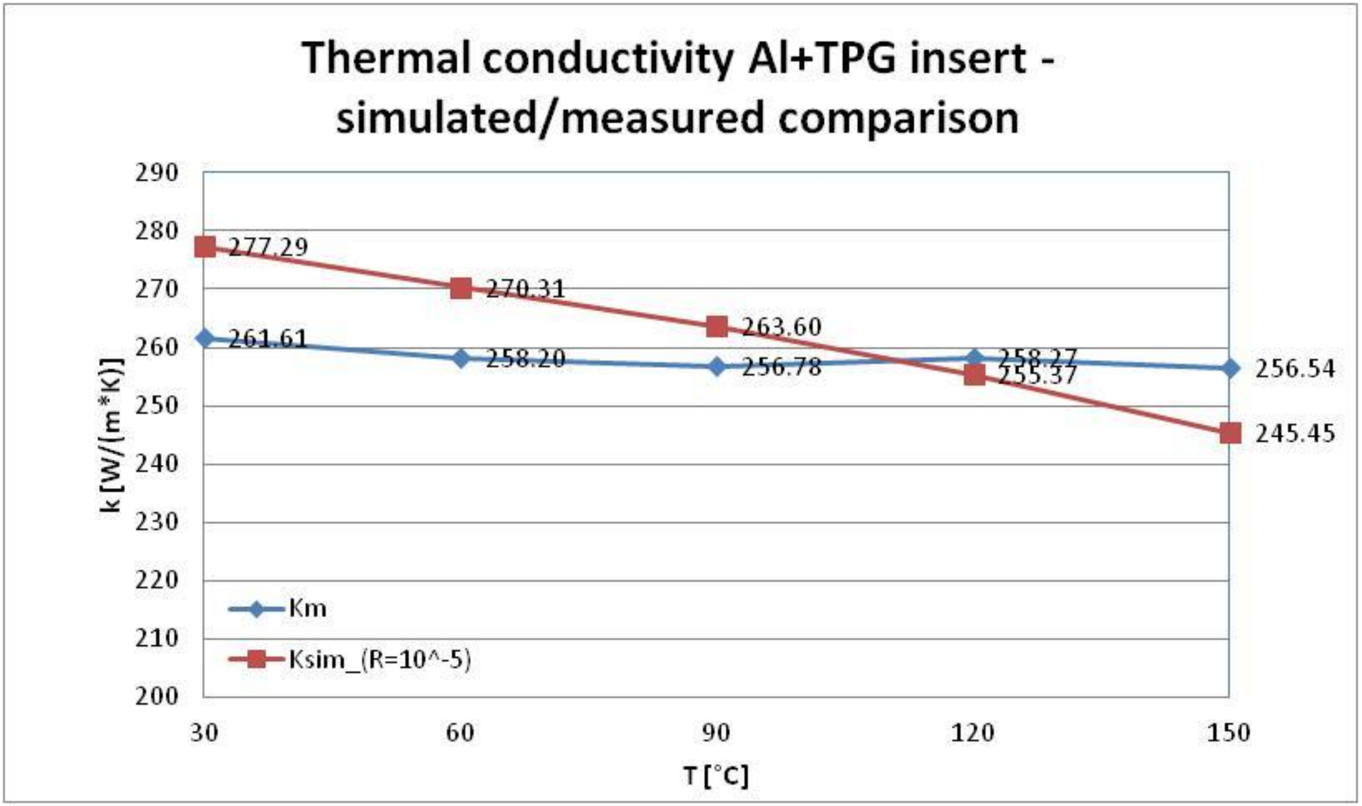
Comparison between numerical results/direct k measurements



	Km [W/(m*K)]	Ksim [W/(m*K)]
T=30°C	261.61	277.29
T=60°C	258.20	270.31
T=90°C	256.78	263.60
T=120°C	258.27	255.37
T=150°C	256.54	245.45

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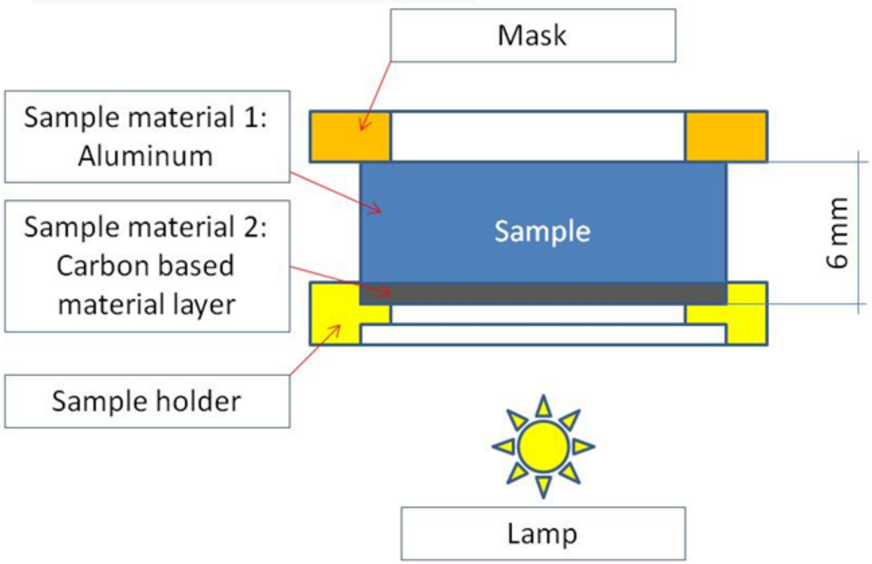
Experimental evaluation of Al-TPG interface thermal resistance

LFA 447 NanoFlash®



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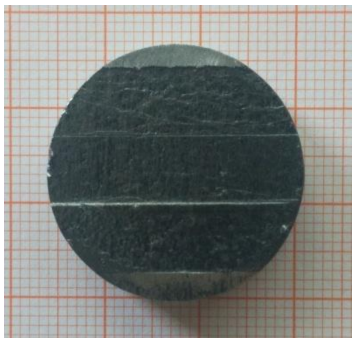
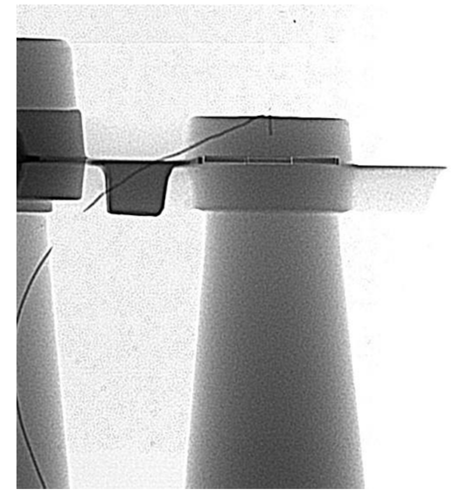
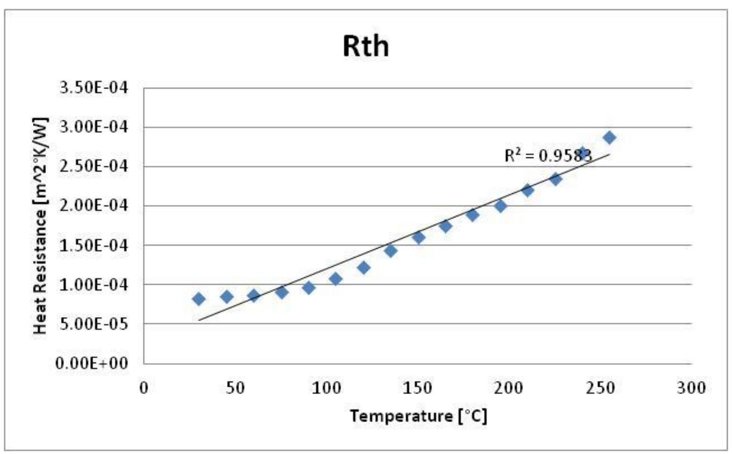
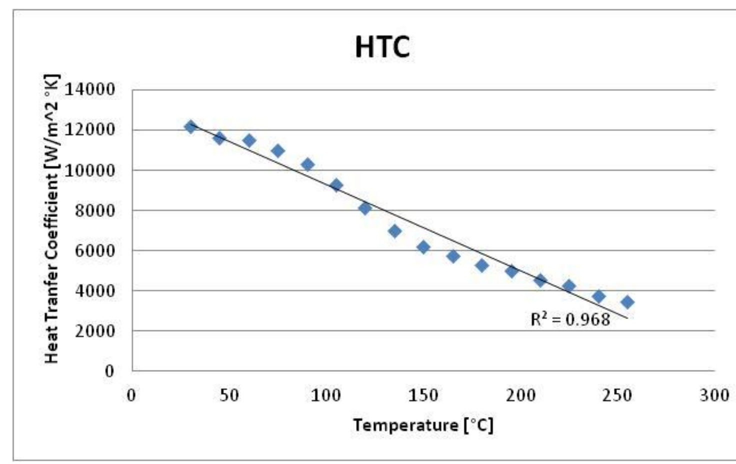
Experimental evaluation of Al-TPG interface thermal resistance









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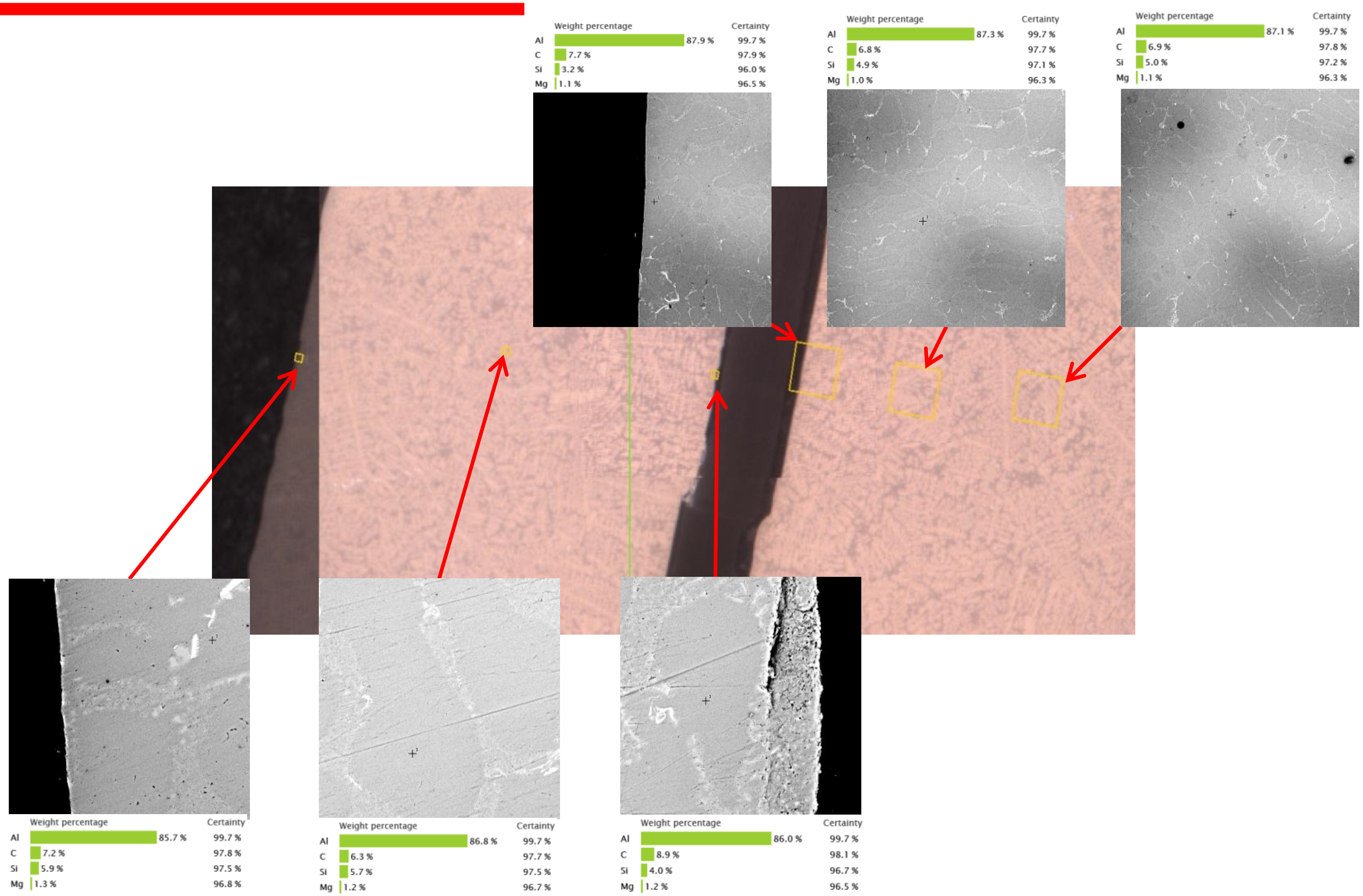
Experimental evaluation of Al-TPG interface thermal resistance



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Conclusions

- FP7 THERMACO Project is aimed at provide manufacturing technologies for extremely efficient solutions in heat evacuation based on Aluminium Metal Matrix Composites (Al-MMC) with Carbon-based thermal highway inserts. The potential applications field of these new composites will targeted to heat evacuation applications in critical fields such as power micro-electronics, e-mobility and (renewable) energy generation as well as highest performance combustion engines.

- Metal process techniques to embed carbon based inserts inside an Aluminum matrix have been adopted producing two different kind of high conductive composites (Al-Diamond particles and Al -TPG inserts)

- The thermal conductivity of the Al matrix has been increased up to 17% in Al-Diamond and about 45% in Al-TPG composite

- The dependence of composite conductivity from the interface thermal resistance between Al matrix and carbon insert was investigated and measured.

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Bibliography

[1] *Poster by Denis Zolotaryov, Prof. Menachem Bamberger, Dr. Alex Katz and Haim Rosenson,* ***Improved Thermal Conductive Aluminium-TPG MMC Produced by Casting – One dimension heat conduction modeling****, Technion, Israel Institute of Technology*

[2] *Poster by Denis Zolotaryov, Prof. Menachem Bamberger, Dr. Alex Katz and Haim Rosenson,* ***Improved Thermal Conductive Aluminium-TPG MMC Produced by Casting*** *, Technion, Israel Institute of Technology*

[3] Heat Conduction / M.Necati Ozisik. – 2nd ed. – John Wiley & Sons, c1993

[4] Momentive, Condensed Product Bulletin, TPG Thermal Management Materials

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Overview and Thank you

- **Consortium:**
  11 partners from 7 countries
- **Duration:**
  09/2013-08/2016
- **Coordination:**
  Technische Universität Chemnitz / Germany

- **Further information:**
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