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The effects of different architectures on thermal fatigue in particle reinforced MMC for heat sink applications

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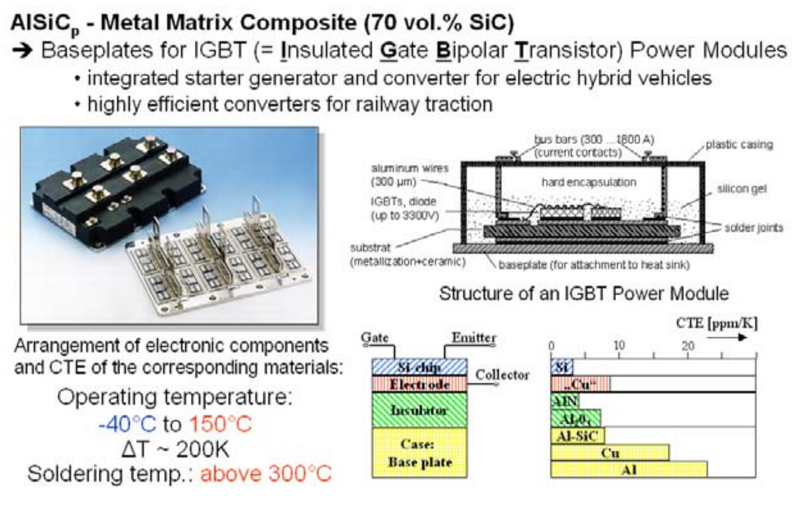
Abstract. Particle reinforced metal matrix composites are developed for heat sink applications. For power electronic devices like IGBT modules (Insulated Gate Bipolar Transistor) a baseplate material with high thermal conductivity combined with a low coefficient of thermal expansion is needed. Commonly AlSiC MMC are used with a high volume content of SiC particles (~ 70 vol.%). To improve the performance of these electronic modules particle reinforced materials with a higher thermal conductivity are developed for an advanced thermal management. For this purpose highly conducting diamond particles (TC ~ 1000 W/mK) are embedded in an Al matrix. These new diamond reinforced MMC were investigated concerning their thermal fatigue mechanisms compared to the common AlSiC MMC. Differences in reinforcement architecture and their effects on thermal fatigue damage were studied by in situ synchrotron tomography during thermal cycling.

Introduction

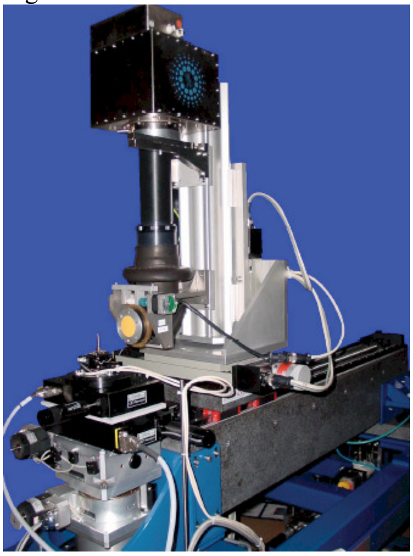
In power electronic applications high power densities are generating heat which has to be transported away from the electronic modules into a heat sink. An advanced thermal management is needed to increase the performance of such modules like IGBTs (Insulated Gate Bipolar Transistors) as shown in Figure.1. The baseplate attached to the ceramic insulator acts prior as heat spreader with a high thermal conductivity (TC) but also has to offer a low coefficient of thermal expansion (CTE) to avoid delamination at the ceramics baseplate interface while cycling thermal loads. For this application Metals are reinforced with ceramics to combine the good TC of a metal with a low CTE of a ceramic. AlSiC MMC are commonly used as baseplate material. In previous measurements an AlSiC7Mg/SiC/70p MMC was investigated concerning residual stresses and void kinetics during thermal cycling

Figure 1:



[1]. The anomalous CTE behavior of AlSiC over 200 °C pointed out as an effect of internal void kinetics during thermal cycling. A system of an interconnected SiC-Si network of reinforcements embedded in an Al matrix could be identified. Residual stresses build up during heating caused by the big thermal expansion mismatch between Al and SiC generate visco plastic matrix deformation resulting in a void closure during heating and reopening during cooling. The void kinetics in the new Al/CD/60p MMC show a different behavior compared to AlSi7Mg/SiC/70p. No indications for interconnections between the diamond particles could be found.

Figure 2:

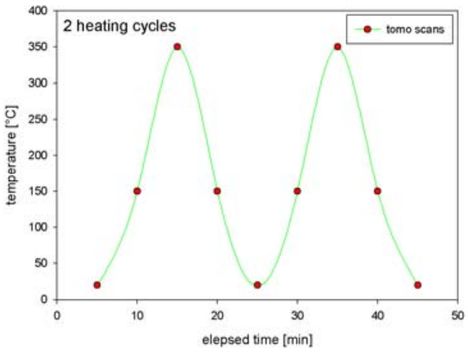


The CCD camera setup at ID19 is shown above. The sample is fixed at a rotation holder and the optics are mounted behind. The CCD camera sits on the top of the movable detector system.

Material

An Al/CD/60p MMC containing of Al 99.99 % and 60 vol.%. diamond particles delivered by EMPA Thun was used for the in situ experiments on ID19 at ESRF Grenoble. The particle size was 25 µm in diameter (monomodal). Due to homogenous infiltration of the small sized samples (0.8x0.8x10) mm³ needed to achieve high 3D resolutions > (0.3x0.3x0.3) µm³ / voxel small particles were used. The higher resolution compared to the earlier AlSiC measurements (ID15A) was necessary to visualize delamination at the interfaces. As cast as well as heat treated (640 °C / 5 h) AlCD samples were investigated concerning the influence of carbide formation on bonding quality between the diamonds and the Al matrix.

Figure 3:

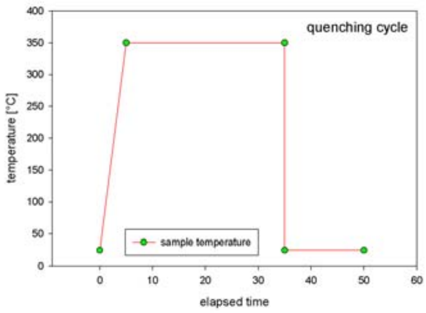


The samples were cycled twice to 350 °C and tomo scans were made at different temperature steps.

Experiment

To visualize the thermal fatigue damage in the Aluminum-Diamond system high resolution synchrotron tomography was carried out during thermal cycling and after quenching. On ID19 this is done by a highly brilliant beam penetrating the sample projecting an absorption contrast image on a CCD camera (Fig.2). The energy of the monochromatic X-ray beam used for absorption contrast imaging of the AlCD MMC was 20 keV. The sample was rotated from 0 to 180° during one measurement. One complete in situ scan consisting of 500 images with a resolution of (0.7µm)³ / voxel took ~ 5 min. For the ex situ measurements with a higher resolution of (0.3µm)³ / voxel one scan took ~ 15 min with 1500 images. During the in situ experiment the sample was heated to 350 °C (soldering temperature) and cooled down to RT two times (Fig.3) and tomography images were taken at different temperature steps. To simulate the worst case scenario for these MMC one heat treated and one as cast sample was heated 350 °C, held for ½ h and quenched to RT (Fig.4). The high resolution tomography was made after this ex situ quenching. Resolution of (0.3µm)³ / voxel was necessary to visualize debonding voids formed at the interfaces.

Figure 4:



The samples were measured ex situ after heating to 350 °C, ½ h holding and afterwards quenching to RT.

Results

The first tomography scan shows an Al/CD/60p MMC delivered by EMPA (Fig.5). The monomodal particles are embedded in an Al matrix. Voids shown in red are mainly formed at the particle matrix interfaces caused by a shrinking matrix during cooling after infiltration. The voids could be segmented and show a volume content of 0.7 vol.% (Fig.6). Compared to an AlSiC volume of the same size (Fig.7) from previous measurements the void volume fraction is significantly higher and mainly arranged at the interface. In the AlCD system the smaller voids arranged at the interfaces with higher volume content are observed.

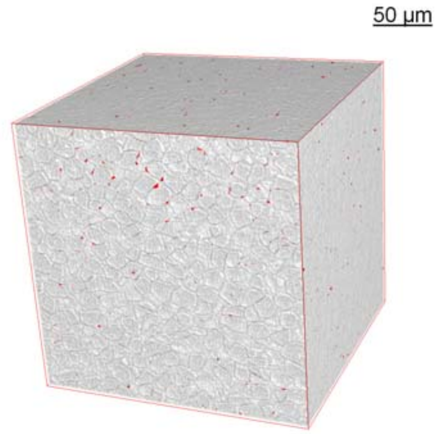
The void kinetics during thermal cycling show an increase of the void volume fraction during heating and a decrease during cooling (Fig.8). The inverse behavior compared to AlSiC [1] could be determined. The AlCD MMC with no additional heat treatment shows a bigger volume increase by weaker bonding at the interfaces. A completely different architecture of reinforcements compared to AlSiC can be expected.

High resolution images of water quenched samples after heating to 350 °C are shown in Fig.9. In the heat treated MMC voids are formed in the matrix between the diamond particles. In the as cast sample, delamination at the interfaces can be observed. The particles are almost completely debonded from the Al matrix after quenching.

Discussion

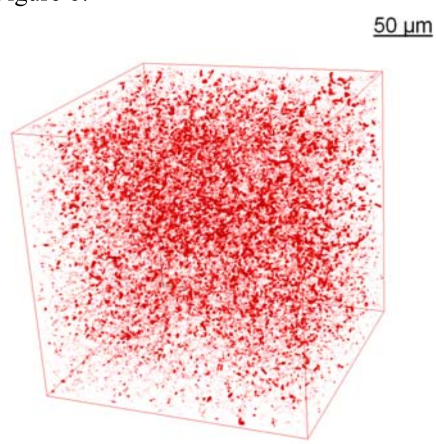
A high volume content of voids of ~ 0.7 vol.% can be observed in the AlCD MMC. These voids origin from incomplete infiltration caused by low wettability of the diamond particles as well as shrinkage of the Al matrix during cooling after infiltration caused by big thermal expansion mismatch (CTE_{Al} ~ 30 ppm/K and CTE_{CD} ~ 1 ppm/K). These voids are mainly arranged at the interfaces due to lower bonding quality compared to AlSiC. The void kinetics during thermal cycling showed a completely inverse behavior of these two MMC. In the AlSiC MMC an interconnected network of reinforcements is formed [1] by Si bridges between the particles. In the AlCD MMC a system of isolated particles in a weak matrix was identified. A superior thermal fatigue behavior of a connected network can be expected by debonding only during cooling and high amounts of radial compressive stresses of the matrix on to the particles during heating inhibiting delamination. In a system of isolated particles the voids do not close during heating lacking compressive stresses in the matrix, but open. As a result debonding occurs during heating as well as during cooling in the AlCD MMC.

Figure 5:



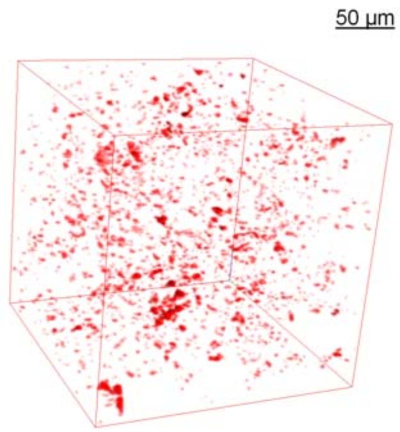
A 200x200x200 µm³ cube is shown above. Voids can be identified at the particle-matrix interfaces (red).

Figure 6:



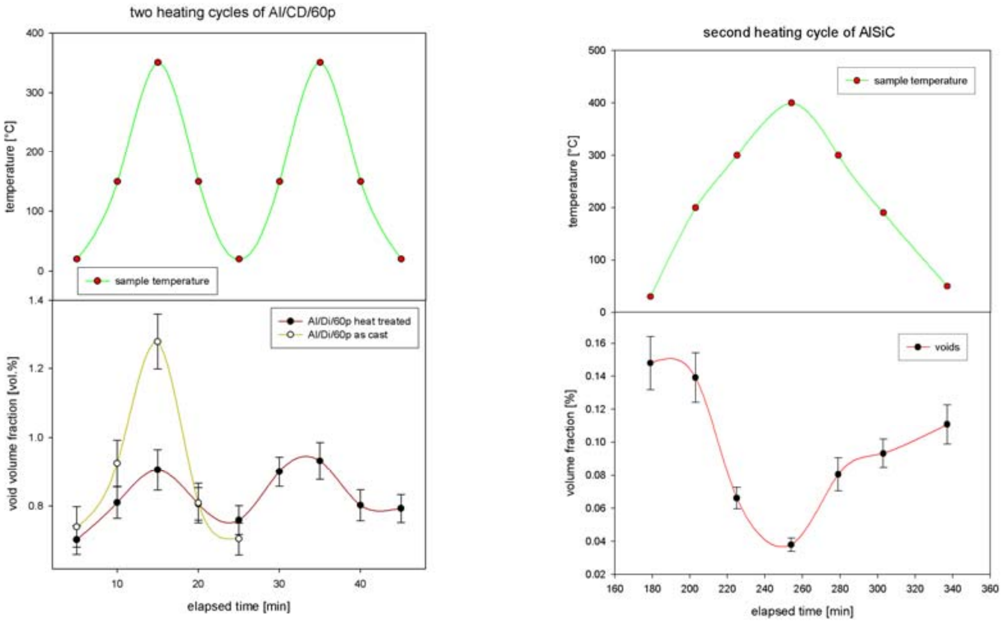
The voids in the AlCD could be separated and appear to be arranged at the interfaces with a volume content of 0.7 vol.%.

Figure 7:



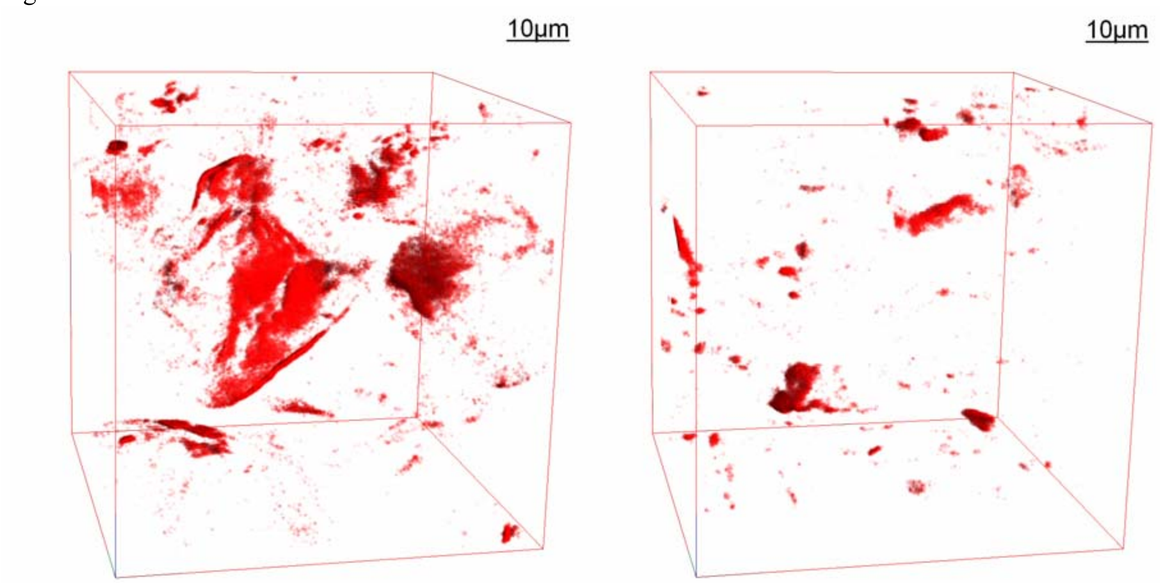
Voids in AlSiC (200x200x200 µm³) show a lower volume content of 0.2 vol.% and a coarser distribution compared to AlCD.

Figure 8:



The void kinetics in an Al/CD/60p MMC are shown on the left during two thermal cycles up to soldering temperature. In the as cast MMC the volume change is higher due to weaker bonding at the interfaces. On the right the void volume fraction changes during a comparable thermal cycle in an AlSi7Mg/SiC/70p MMC are shown [1]. An inverse behavior of the void volume fractions could be observed.

Figure 9:



On the left the voids in an as cast AlCD MMC are shown after quenching from 350 °C (soldering temperature) to RT. Almost completely debonded diamond particles from the Al matrix can be observed. On the right the voids in a heat treated (640 °C 5h) AlCD MMC after quenching from 350°C are separated. In this case the voids are formed in the matrix and less delamination voids at the interfaces can be seen due to better bonding quality.

An improvement of the interface bonding quality by carbide forming heat treatments of the AlCD MMC is proved through high resolution tomography of quenched samples. Delamination at the particle interfaces are caused by a rapid shrinking matrix during cooling.

Conclusion

Metal matrix composites reinforced with ceramics are developed for heat sink applications. The big mismatch in thermal expansion produces high amounts of residual stresses during temperature changes. Voids are formed during cooling after infiltration by matrix shrinkage. In situ investigations of void kinetics during thermal cycling show plastic deformation due to stress induced visco plastic matrix deformation (creep). High resolution synchrotron tomography enables a calculation of the void volume changes in situ which allows an understanding of the effects of different reinforcement architecture on the thermal fatigue behavior of such MMC. In the case of AlSiC an interconnected network of SiC particles connected by Si bridges could be identified. In the AlCD MMC a system of isolated particles reduce the thermal stability concerning fatigue damage at cycling thermal load compared to AlSiC. In situ stress evaluation combined with tomography like for AlSiC has to be done on AlCD to show elastic as well as plastic matrix deformation critical for the long term stability of these MMC. With high resolution tomography delamination between matrix and reinforcements can be visualized by void segmentation. Interface design of PRM like heat treatments in the AlCD system improve bonding quality but do not affect the reinforcement architecture important for thermal fatigue damage.

References

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