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Executive Summary Report

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Additive Manufacturing of Intricate Reaction Bonded Silicon Carbide Components For Aerospace Applications

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The process used for the production of reaction bonded silicon carbide (RBSC) materials via laser powder bed fusion (LPBF) is schematically shown in Figure 1. It is a powder metallurgy (PM) process that consists of four steps [1]. The first step is powder preparation. Silicon and silicon carbide powders are homogeneously mixed. In the second step, the obtained powder mix is shaped using an additive manufacturing (AM) technique, namely LPBF. Thin layers of powder are spread on a build platform and selectively scanned with a laser. The consolidation mechanism consists of melting and re-solidification of the silicon, which acts as a metal binder to fuse the silicon carbide particles together into a porous preform containing both Si and SiC. The third step then, consists of carbon infiltration into the porous Si-SiC preform. This is done via a phenolic resin, which is first loaded into the preform, and subsequently pyrolysed at elevated temperature, leaving behind a large amount of residual carbon. Finally, the C-Si-SiC preforms are infiltrated with liquid Si at temperatures in excess of 1450°C. The silicon reacts with the added carbon to a reaction formed SiC, and fully densifies the preforms. This results in fully dense reaction bonded silicon carbides with high SiC fractions. In addition, since liquid metal infiltration is used instead of solid state sintering, shrinkage is effectively avoided, and the process is a net-shaping process. This process can also be used for reaction bonded boron carbides.

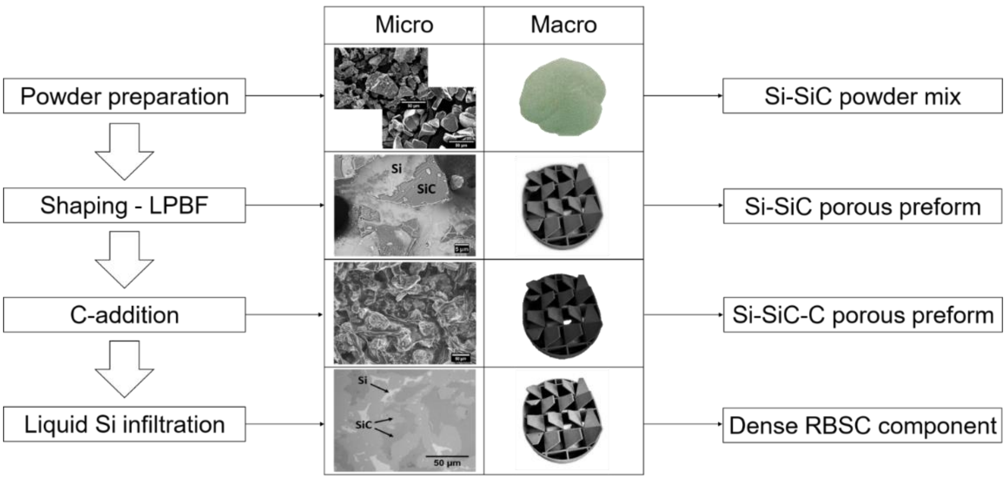

Figure 1: powder metallurgy process for the fabrication of reaction bonded silicon carbide via laser powder bed fusion.

Surface roughness of the final reaction bonded silicon carbide components is an important property and should be kept as low as possible, since it determines the final mechanical strength and industrial applicability of the production technique. Surface roughness was assessed after laser powder bed fusion (LPBF). It was found that roughness is directly linked to porosity, and therefore the parameter set that yields the most dense components after LPBF also leads to the lowest surface roughness. The optimal powder mix consists of 40 vol% Si powder and 60 vol% SiC powder. The optimal LPBF parameter set uses a laser power of 15 W combined with a scanning speed of 100 mm/s. Defocusing and re-melting were found to have no effect, and so were omitted, since they only add to processing time. The lowest achieved surface roughness after LPBF was 17,2 µm.

The effect of post-processing on surface roughness was also assessed. Omitting the carbon infiltration step, and only performing liquid silicon infiltration, leads to a decrease in surface roughness. However, if carbon infiltration was performed, the surface roughness increased, and it increased even more after liquid silicon infiltration, up to 33.8 µm Ra. The carbon infiltration step is therefore a crucial step with respect to the surface roughness. The components should be cleaned after carbon infiltration and prior to Si infiltration in order to limit adverse effects of excessive surface roughness.

In order to gain knowledge on the type of structures that can be produced using laser powder bed fusion of Si-SiC, as well as on the dimensional limitations of the process, geometrical benchmark components were designed. These geometrical benchmarks contain a number of features of interest. Through-holes and straight and curved channels were successfully produced with minimal dross formation. Minimal feature sizes were down to 250 µm, and there is no shrinkage between design and final component.

Another important aspect to dimensional limitations is the maximum overhang angle which can be achieved without the need for support structures. The maximum angle which can be achieved without supports is 70° with respect to the vertical axis. For angles larger than these 70 degrees, different support geometries were tested by building bridge structures. The only successful result was obtained with a fragmented block geometry. This is a support structure which is bulkier than the ones used for metal LPBF, but is necessary due to the brittle and porous nature of the Si-SiC structures. The optimal z-offset between the bottom of the supported area and the top of the support structures was found to be 120 µm, after measuring surface roughness values of the supported areas post support removal.

For the optimisation of the mechanical properties, 3-point flexural test bars (4.5 x 3.5 x 45 mm^3) were built using the Si-SiC 40:60 vol% powder mix under a 45 degree angle, and with the optimal parameters for surface roughness minimisation. Mechanical properties were assessed via Weibull statistics. The “as-built” beams had a Weibull modulus of 6.7 and a characteristic strength of 148 MPa, whereas similar post-processed (surface machined) beams had a higher Weibull modulus of 7.9 and a characteristic strength of 175.1 MPa. This highlights the importance of surface roughness. In order to further improve the process, either a surface finishing method for complex surfaces should be investigated, or surface roughness should be further minimised by cleaning components after carbon infiltration.

Given the limitation with respect to mechanical strength due to the inherent surface roughness of LPBF Si-SiC components, possible applications for LPBF Si-SiC should take advantage of other desirable properties of the material, such as the high thermal conductivity, low thermal expansion coefficient and high corrosion and wear resistance. One such an application are heat transfer devices, such as heat exchangers and heat sinks. In addition, the enormous design freedom that comes with additive manufacturing can be used to create complex components with a high surface-to-volume ratio. Triply periodic minimal surface (TPMS) structures, such as gyroids, are a prime candidate geometry for heat transfer devices. They cannot be fabricated by traditional manufacturing techniques, especially for ceramic materials. A Si-SiC gyroid heat sink therefore perfectly combines the advantages of additive manufacturing with the high thermal conductivity of the Si-SiC material.

In order to pinpoint the feasibility of a Si-SiC gyroid heat sink, it was compared to two other gyroid heat sinks, i.e. one in an aluminium alloy and one in pure copper. All three heat sinks were produced via LPBF, and are presented in Figure 2. The footprint of the heat sinks is 40x40 mm², and the unit cell size is 8x8x8 mm³.

Figure 2: Gyroid heat sinks in three different materials, produced by LPBF. From left to right: Al-Cu alloy, Si-SiC, pure Cu.

The produced heat sinks were tested in an in-house built set up, where thermal transmittance was tested as a measure for the amount of heat transferred from the heat sink to water flowing through the heat sink. It was found that Si-SiC performed better than aluminium, but worse than copper. However, when normalised by weight, aluminium and Si-SiC perform similarly and vastly better than copper, as presented in Figure 3. Finally, Si-SiC can also withstand higher temperatures up to 1400°C. It could be interesting to compare the gyroid heat sink to a more traditional fin/strip design, in order to map the added value of additive manufacturing . However, it is clear that a gyroid structure should outperform more simplistic designs. This case study proves that there is significant potential in using LPBF Si-SiC material in heat transfer applications. Additive manufacturing of Si-SiC opens up a lot of avenues, especially for space applications in very hostile environments with extreme temperatures, as Si-SiC gyroid heat exchangers with internal cooling channels can be used.

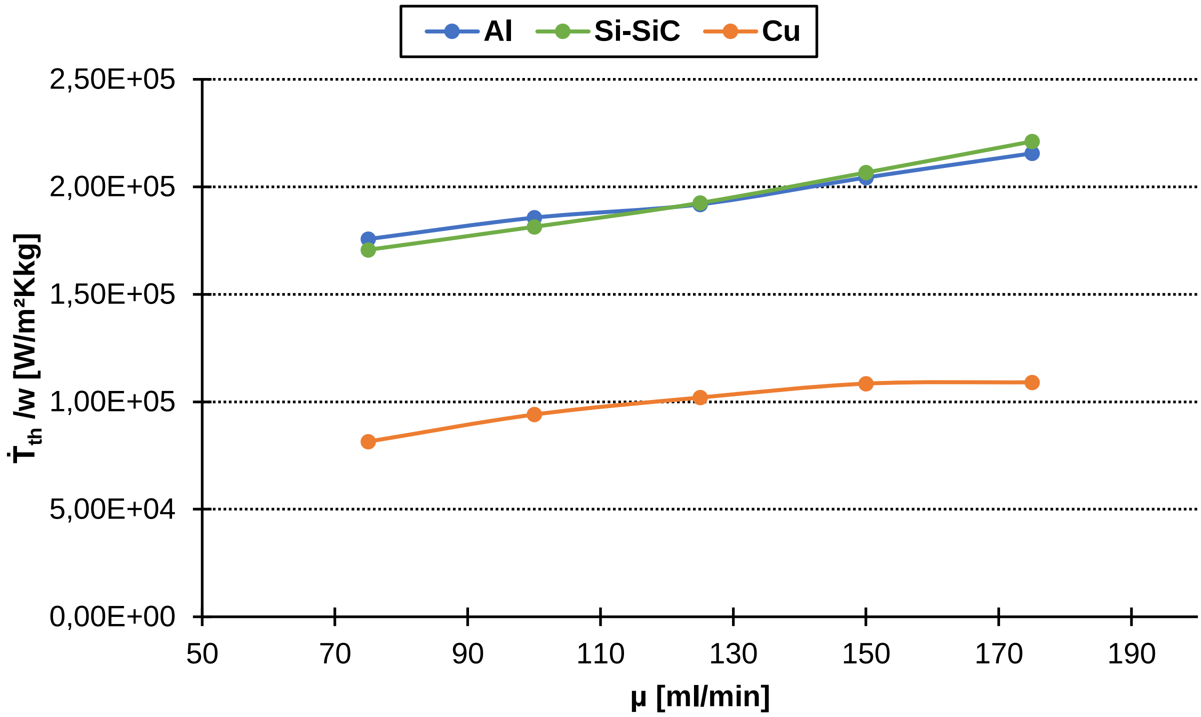

Figure 3: Normalised thermal transmittance for aluminium, Si-SiC and copper heat sinks. The specific thermal transmittance of copper is lowest, due to its highest weight. Aluminium and Si-SiC perform very similarly.