Environmental Impact Assessment of Manufacturing of SiC/SiC Composites

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Abstract. SiC/SiC composites have attracted increasing attention in various applications such as turbine blades, exhaust nozzles, and combustor chambers, due to their exceptional mechanical and thermal properties. However, the environmental impact of these composites across their life cycle is an important aspect that needs to be evaluated to support their responsible development and use. In this study, a life cycle assessment of SiC/SiC woven laminate ceramic matrix composites to quantify their environmental impacts from cradle-to-gate was conducted. Three different manufacturing methods to produce SiC/SiC woven laminates were researched: chemical vapour infiltration (CVI), pyrolysis of a preceramic polymer (PIP), and melt infiltration (MI). The Life Cycle Assessment approach was utilized to identify the effect outcomes for each process, analysing the raw material extraction, raw material processing, and final product manufacturing phases to develop the environmental impact assessment. The study's outcome showed that CVI had the lowest average environmental impact between the two methods.

Keywords: SiC/SiC Ceramic Matrix Composites · Life Cycle Assessment · Environmental Impact

1 Introduction

Silicon Carbide/silicon Carbide (SiC/SiC) Ceramics Matrix Composites (CMCs) Have Emerged as a Promising Class of Materials Due to Their Exceptional Mechanical Properties, High-Temperature Stability, and Corrosion Resistance [1]. These Materials Are Composed of SiC Fibres Embedded in a SiC Matrix. SiC/SiC CMCs Have the Potential to Replace Conventional Materials in Demanding Applications, Leading to Improved Performance Due to Their Lighter Weight and Thermal and Mechanical Properties [2]. However, a Comprehensive Understanding of the Environmental Implications Associated with Producing SiC/SiC CMCs is Essential for Their Sustainable Deployment.

The application of SiC/SiC CMCs has been growing steadily in aerospace, nuclear, and other high-temperature industries due to their exceptional thermal and mechanical properties. However, despite their widespread use, there has been a notable scarcity of LCA studies focusing specifically on SiC/SiC CMCs. This research aims to bridge this

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gap by conducting a thorough evaluation of the environmental implications associated with the production of these materials.

This study aims to evaluate the environmental impacts of SiC/SiC composite manufacturing processes by comparing three possible manufacturing methods: Chemical Vapor Infiltration (CVI), Polymer Infiltration Pyrolysis (PIP), and Melt Infiltration (MI). The choice among these methods depends on factors such as ease of application, industry applicability, and end-product quality [3]. CVI is complex and technically demanding, suitable for high-performance SiC/SiC composites in aerospace, nuclear, and high-temperature applications, but may have limited use in small-scale or custom manufacturing [4]. PIP is more accessible and adaptable than CVI, commonly used in aerospace, automotive, and energy industries, producing composites with good properties. However, residual carbon can limit operating temperature and increase oxidation risk [6–8]. MI involves infiltrating a preheated fibre preform with a molten infiltrant material, commonly used in aerospace and high-performance applications for dense composites with excellent properties [9–11].

To assess their environmental impacts, Life Cycle Assessment (LCA) methodology is employed. LCA evaluates environmental impacts throughout a product's life cycle, considering energy consumption, materials, water usage, and waste generation [12–15]. It helps identify environmental hotspots, informs decision-making, and aids in product design, process optimisation, material selection, and waste management [15].

The outcomes of this study provide valuable insights into the environmental performance of SiC/SiC CMCs and facilitate informed decision-making for material selection, process optimisation, and sustainability improvements. The findings contribute to the growing body of knowledge on advanced composite materials and support the development of more sustainable and environmentally friendly manufacturing practices.

2 Methodology

The LCA approach employed in this study adheres to ISO 14040 and 14044 standards, which provide a systematic framework for analysing the environmental consequences of products throughout their life cycle. The approach involves four major stages: aim and scope definition, inventory analysis, impact assessment, and interpretation [16].

2.1 System Boundary

The system boundaries of the LCA study encompass the raw material extraction, material manufacture, and product manufacture stages. Figure 1 shows that SiC fiber and matrix are input materials for each method. Manufacturing of these input materials is encompassed in the LCA study and the manufacturing of composite materials using three different manufacturing methods is analysed separately. The functional unit is defined as 1 kg of SiC/SiC woven laminate, which serves as the reference unit for all impact assessments. The size and mechanical properties of the end product are not specified as these are out of the scope, and they do not impact the impact assessment results.

The environmental impact categories considered in the assessment include various midpoint indicators. The impact assessment methods employed are based on widely

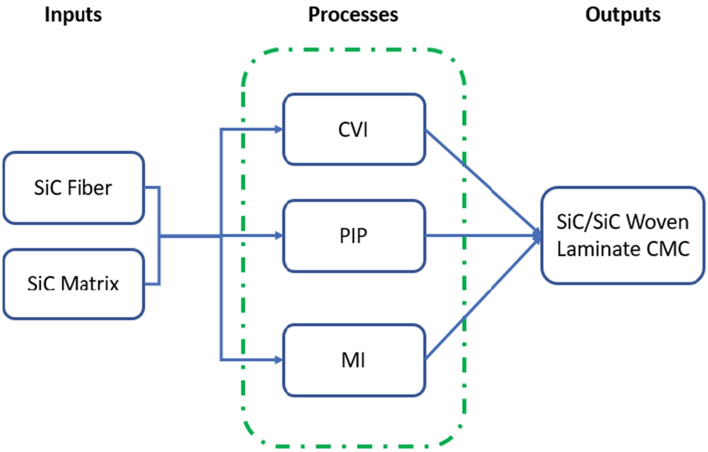

Fig. 1. System boundary for SiC/SiC woven laminate CMC manufacturing.

recognised characterization models and indicators, such as the ReCiPe method [17]. These methods enable the quantification and comparison of impacts across different environmental categories.

2.2 LCA Inventory

The data used in this study are sourced from up-to-date databases, scientific literature, industry reports, and manufacturers' specifications (20, 21). Specific assumptions are made in the result section to account for uncertainties and process hot spots, ensuring a comprehensive analysis. The inventory data include energy consumption, material inputs, emissions, waste generation, and transportation requirements at each life cycle stage.

The production processes for SiC/SiC CMC materials involve several key steps. These include the production of SiC base matrix material, the manufacturing of SiC fibres, and the weaving of SiC fibres into a laminate structure. Each process contributes to the production of SiC/SiC CMC materials and is crucial in determining their environmental impacts.

For the life cycle investigation, the different processes, materials, solvents, additives, and waste were accounted for 1kg of SiC/SiC composite material. More specifically, CVI process steps included the preparation of the fibre preform, the placement of the preform in a CVI reactor, the introduction of precursor gases, such as silicon-containing and carbon-containing compounds, chemical reactions on the surface of the preform to deposit SiC matrix material, repeated cycles of gas introduction and reaction to achieve the desired matrix thickness and the machining and finishing steps as shown in Fig. 2 [18, 19]. CVI does not typically involve the use of solvents. Waste gases, such as unused precursor gases, reaction by-products, and excess gases, may be generated [22].

With regards PIP, the first steps are the preparation of the fibre preform, impregnation of the preform with a preceramic polymer solution, the removal of the excess polymer solution from the preform, pyrolysis of the impregnated preform to convert the polymer

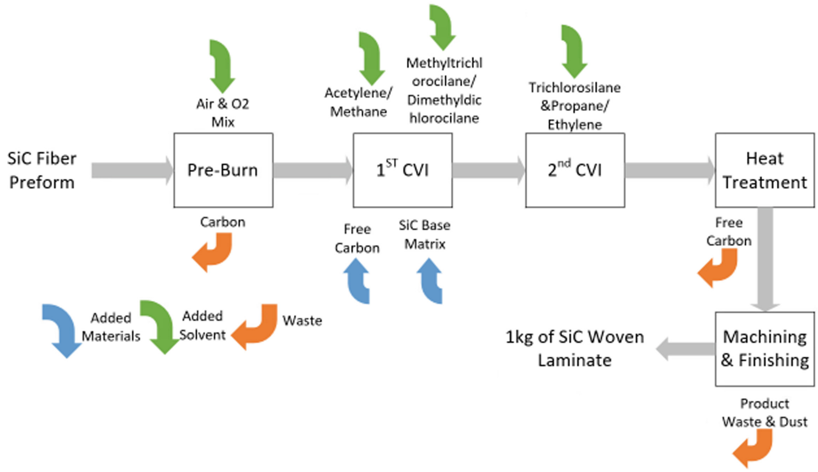

Fig. 2. SiC/SiC Woven Laminate CMC creation with CVI process.

into a SiC matrix, thermal treatment to achieve the desired matrix properties, and cooling and finishing steps as it can be seen in Fig. 3 [23, 24]. Common solvents used in PIP may include organic solvents, such as toluene or xylene, for dissolving the preceramic polymer. Waste solvents, excess polymer solution, and by-products of pyrolysis, such as gases and volatile organic compounds (VOCs), may be generated [25].

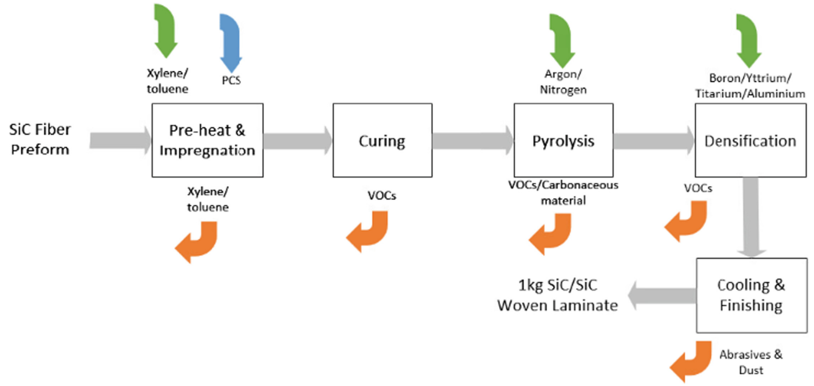

Fig. 3. SiC/SiC Woven Laminate CMC creation with PIP process.

MI process steps include the preparation of the fibre preform, preheating of the preform to a temperature suitable for infiltration, introduction of a molten infiltrant material, such as silicon or silicon alloy, infiltration of the molten material into the preforms void spaces, solidification and cooling of the infiltrated preform, removal of any excess infiltrant material and cooling and finishing steps as it can be seen in Fig. 4 [26, 27]. MI does not typically involve the use of solvents. Waste infiltrant material, excess infiltrant material, and any solidified or residual infiltrant may be generated as waste.

The life cycle inventory (LCI) results provide valuable insights into the energy consumption, material inputs, and emissions associated with the production of SiC/SiC CMC materials. Energy consumption data include the energy required for each process step, such as furnace heating, mixing, spinning, densification, and cooling. Material inputs encompass the quantities of raw materials, chemicals, and consumables used throughout production. Emissions data capture the release of greenhouse gases, air pollutants, and other substances resulting from the manufacturing processes.

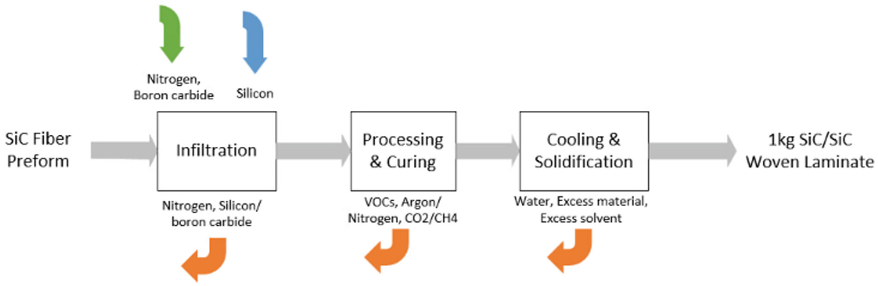

Fig. 4. SiC/SiC Woven Laminate CMC creation with M.I. process

In addition, the results allow for a comprehensive analysis of the environmental impacts associated with SiC/SiC CMC materials. This analysis encompasses various impact categories such as global warming potential, acidification potential, eutrophication potential, ozone depletion potential, and human toxicity. Additionally, resource depletion indicators can provide insights into the depletion of non-renewable resources throughout the life cycle.

3 Results

For each of the manufacturing processes illustrated in Figures, 2, 3, and 4, every step was researched separately in terms of operating temperature, time, energy consumption, solvent materials used, and occurring waste. This allows calculating and comparing the different impacts of each process regarding global warming, freshwater ecotoxicity, ionizing radiation, marine ecotoxicity, human carcinogenic, fossil resource scarcity, and landfill use. When comparing the environmental impacts between CVI, PIP, and MI processes, the highest values in these categories indicate that these processes have a relatively greater potential environmental impact than the others. The contributions of the base matrix, woven fabric, and other steps on the Endpoint Ecosystem impacts of each process are presented in Fig. 5 for each stage of the CVI, PIP, and MI processes.

In all three processes (CVI, PIP, MI), the SiC base matrix is the main contributor to the environmental impact, involving energy-intensive steps in its manufacturing. The creation of the SiC base matrix contributes significantly to the overall environmental impact of each process.

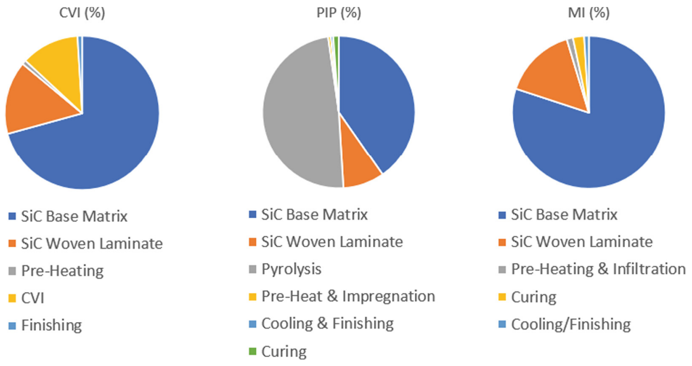

Fig. 5. Contribution of each manufacturing phase to the Environmental Impact

In the MI process, the SiC base matrix has a high impact due to the energy-intensive melt infiltration step. Similarly, in CVI, material selection and usage efficiency are crucial as the SiC base matrix significantly impacts the process.

The PIP process has a hotspot in the Pyrolysis stage, leading to a relatively higher environmental impact. However, the SiC Woven Laminate stage has a comparatively lower impact, which is a positive aspect.

Overall, reducing the environmental impact of the SiC base matrix remains a key focus in all processes. CVI shows a more evenly distributed impact, suggesting it may be a more environmentally friendly choice compared to PIP and MI.

According to Fig. 6 environmental impact results, it is evident that MI has the highest impact in terms of Ionizing Radiation. Whereas PIP has the highest impact in terms of Terrestrial Ecotoxicity, Marine Ecotoxicity, HCT, Freshwater Ecotoxicity, Land Use, and Fossil Resource Scarcity. Moreover, CVI has the highest Global Warming impact. From Fig. 6, it is concluded that PIP has the highest environmental impact of the compared manufacturing processes based on the compared indicators. Conversely, CVI consistently shows lower environmental impacts across most categories, making it a favorable option in terms of environmental sustainability. Overall, based on the provided data, CVI seems to be the most suitable process for the fabrication of SiC/SiC composites, considering its lower environmental impact in multiple categories.

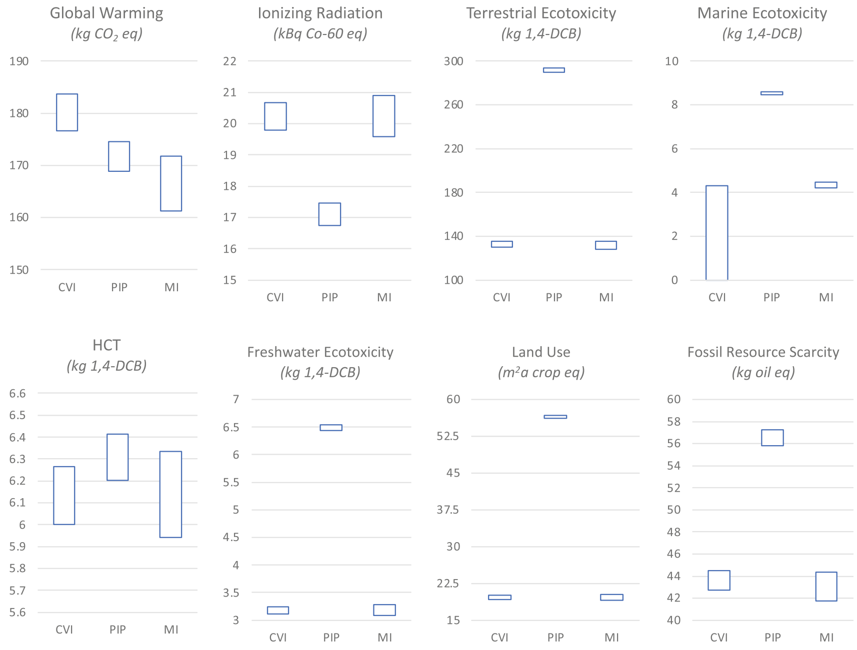

Fig. 6. Environmental Impact Assessment results.

4 Conclusion

In this study, the environmental impact of three different manufacturing processes of SiC/SiC CMCs was evaluated and compared. This study reveals the environmental profile of SiC/SiC CMC materials throughout the raw material extraction, the manufacturing processes, and the manufactured product. It summarizes the key findings related to, greenhouse gas emissions, resource depletion, and other environmental impact categories. The summary highlights the significant contributions of different life cycle stages to the overall environmental footprint of SiC/SiC CMC materials.

The study reveals distinct environmental impacts among the three manufacturing processes. CVI generally shows lower impacts than PIP and MI, suggesting potential environmental benefits. PIP has the highest environmental effect across most impact categories, while CVI has the lowest impact. MI falls between PIP and CVI in terms of overall environmental impact.

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