



Manufacturing of a CMC scramjet inlet insert for flight applications

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Abstract

Hypersonix Launch Systems (HLS) is an Australian start-up aiming to launch a 3D-printed hypersonic vehicle by the end of 2025. The vehicle's structure, including both the engine and airframe, will predominantly utilize Inconel due to its high-temperature resistance. However, thermal modelling conducted by HLS identified a critical region within the engine intake that would be exposed to heat loads exceeding Inconel's tolerance. To address this, HLS partnered with The University of Queensland to investigate the feasibility of manufacturing a ceramic matrix composite scramjet inlet- insert. Although the Ceramic Matrix Composite (CMC) crotch insert could have been fabricated entirely from a machined CMC plate, this method was deemed cost-prohibitive and time-intensive. Instead, the project focused on producing the component as close to near-net shape as possible, thereby minimizing the extent of final machining required. Several manufacturing challenges emerged that significantly influenced design decisions. The initial strategy employed the Polymer Infiltration Pyrolysis (PIP) process, selected for its simplicity and lack of requirement for ultra-high temperature furnaces. However, extended turnaround times between specimen cycles and insufficient mechanical properties necessitated a transition to reactive melt infiltration. The manufacture of a flight ready scramjet inlet-insert was successfully demonstrated. In this paper we describe the development journey and summarise the findings.

Keywords: *Ceramic Matrix Composite, Reactive Melt Infiltration*

Nomenclature

Latin

CMC – Ceramic Matrix Composites
RMI – Reactive Melt Infiltration

CVI – Chemical Vapour Infiltration
PIP – Polymer Infiltration Pyrolysis

1. Introduction

Nickel-based super alloys, renowned for their exceptional high-temperature resistance, have been a pivotal material in the aerospace for applications such as turbine blades or combustion chambers [1, 2]. In addition of having been proven in application, super alloys such as Inconel can be 3D printed. Consequently, Hypersonix Launch Systems, an Australian startup, has made the strategic decision to incorporate Inconel into the construction of its engine and airframe. However, as hypersonic flights become more prevalent, a critical challenge to address is the material selection for the vehicle. While super alloys provide greater manufacturing flexibility, thermal loads in the hypersonic regime flight present a significant material challenge. While numerous generations of super alloys have been developed, each exhibiting enhanced resistance through the incorporation of ruthenium and rhenium, the aerodynamic heating generated during hypersonic flight can surpass the limits of super alloys, with the equilibrium stagnation point temperature in air-breathing vehicles can reaching 3000-4000K [1, 3]. These temperatures exhibit varying intensity and location depending on the flow path, presenting a case study for each section of the vehicle .

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In such harsh conditions, ceramic matrix composites (CMCs) are typically the preferred material. However, they also pose challenges. The manufacturing of components with intricate 3D shapes is not straightforward, and constructing the entire vehicle using UHT-CMC would be very costly. Therefore, in this research, CMCs were utilized in conjunction with 3D-printed Inconel. The engine was 3D printed, providing exceptional flexibility, while the scramjet inlet was fabricated from CMC. In the Australian context, there is a limited research on the interaction between a CMC component and super alloy components at high temperatures. The integration of CMC components having complex 3D features with other materials necessitates the exploration of methods to manufacture CMC with limited machining. Thus, the use of a near net shape manufacturing process was used to produce a scramjet inlet that can be integrated into a 3D printed air breathing hypersonic vehicle.

2. Method

2.0.1. Thermo-structural Modelling

DART, a high temperature alloy, hydrogen fuelled scramjet technology demonstrator, flies a trajectory which leads to a transient thermal boundary condition on the vehicle. Mach number, dynamic pressure, and angle of attack all vary significantly with time over the course of the trajectory. A thermal deck of viscous computational fluid dynamics simulations of each of the predicted states of the whole vehicle were run to obtain the heat transfer coefficient and the recovery temperature of the flow. The convective boundary condition and driving temperature were then mapped every second onto the inlet insert and the transient response was then simulated. Two approaches to the structural simulation were taken. The first approach kept computational runtime and model complexity low by simulating the insert in isolation with three point-constraints to prevent rigid body movement only. This was particularly useful in the early stages of the project to assess viability of candidate material systems. The second approach was a higher fidelity model that included the surrounding region of the inlet and replicated the transient response of both the CMC inlet insert and the Inconel surrounds. Again, rigid body movement was prevented via three point-constraints. Acceptance tests and limit strengths were derived from the second approach. Initially, the mechanical and thermal properties of the CMC were taken from literature. When the conductivity, specific heat capacity, density, and flexural strength of the candidate material were determined from testing, the simulations were rerun to confirm suitability.

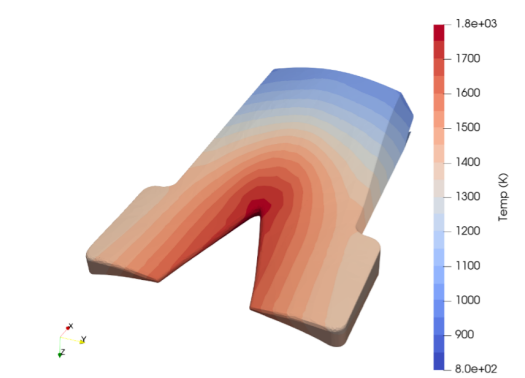


Fig 1. Temperature map of the scramjet inlet insert

Similar materials have been shown to be suitable in Mach 6 flow for 135 seconds with minimal recession [4]. For the current CMC component, two separate tests were performed. The first was to confirm high temperature suitability of a witness coupon and that no unexpected behaviour occurred when the specimen was subject to a high heat flux via an oxy-acetylene torch. The second test was a purely mechanical test with the goal to emulate the stress concentration seen due to the thermal gradients with a simpler loading arrangement. Through FEA a compression force on one of the “sleeves” of the insert was found to closely emulate the stress concentration found in the notch of the inlet insert. This load case was then replicated on a universal testing machine and to formed part of the hardware acceptance tests.

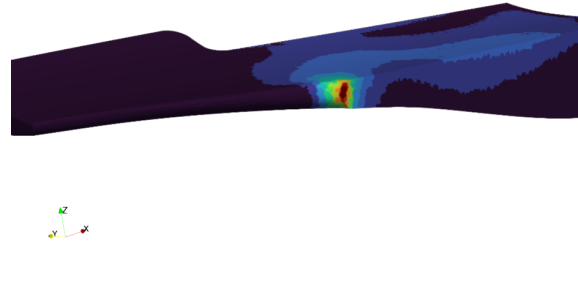


Fig 2. Cross section of the stress state scramjet inlet at peak temperature

2.0.2. Polymer Infiltration Pyrolysis method

The University of Queensland is relatively new to the CMC field, and the PIP process was, at the time, the method the team was most acquainted with. The polymer infiltration pyrolysis, also known as the PIP process, is a method employed to manufacture CMC through the pyrolysis of silicon polymers. The composite is initially prepared using conventional polymer manufacturing processes before being subjected to pyrolysis at 1100°C, resulting in the formation of an amorphous ceramic phase. This phase can subsequently be crystallized by elevating the pyrolysis temperature to approximately 1600°C, thereby producing a CMC with enhanced thermal properties. The specimen can then be reinfiltreated with the resin to reduce the porosity until it reaches a plateau.

The design of the crotch was intended to use a highly conductive material to effectively dissipate heat away from the inlet to the inconel engine. Therefore, the material was pyrolysed at 1000°C and 1700°C halfway through and at the final PIP stage to yield the β -SiC phase, which exhibits superior thermal conductivity [5, 6]. Furthermore, the green body was fabricated using a slurry made of polycarbosilane resin and β -SiC powder. The addition of SiC powder aimed to improve both ablation resistance and thermal conductivity, while the large number of PIP cycles (14 in total) served to lower porosity and thereby maximize thermal conductivity.

Thermal conductivity The material's conductivity was one of the primary driving properties. The latter was kindly tested by the Defence Science and Technology Group (DSTG Melbourne) using a laser flash (Netzsch 427, Germany). The diffusivity was determined using a LFA with three measurements per temperature. The specific heat capacity (C_p) was measured on a DSC, and the density change was corrected using a thermo-mechanical analyser (TMA). The thermal conductivity was calculated by multiplying the diffusivity, density, and heat capacity. The results are presented in Figure 3.

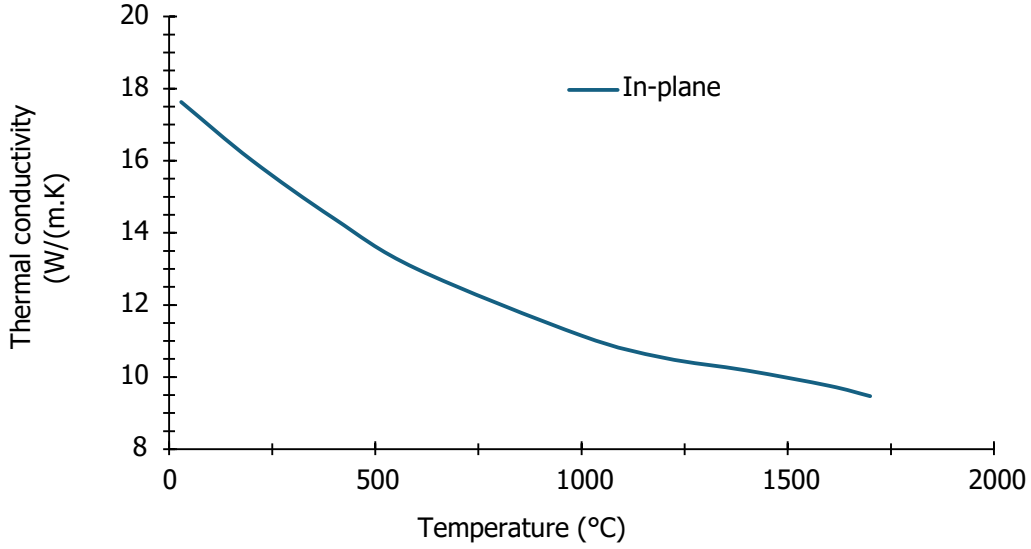


Fig 3. Thermal conductivity of C/SiC made via Polymer Infiltration Pyrolysis

The thermal conductivity showed a consistent downward trend across the measured temperature range, decreasing from nearly 18 W/(m·K) at room temperature to about 9.5 W/(m·K) at 1700°C. Reported thermal conductivity at room temperature vary between 10 to 330 W/(m.K), so these values fall within the range reported in the literature [7], although they could have been higher. The measured porosity, approximately 11%, is a likely cause. It is widely acknowledged that developed pores hinder the propagation of phonons. Despite the presence of a high number of PIP, this porosity may have originated during the high-temperature pyrolysis process. SiC-derived polymers are known to undergo carbothermal reduction around 1400°C [8, 9, 10].



Heat transfer in these materials occurs primarily through lattice vibrations, which are quantized as phonons. At pore interfaces generated during carbothermal reduction, phonon scattering significantly hinders thermal conduction. Consequently, C/SiC composites derived from polymer precursors—despite the incorporation of SiC powder—inevitably develop macropores, leading to enhanced phonon scattering. Furthermore, the crystals formed during high-temperature pyrolysis remain relatively small, around 6 nm, which also contributes to reduced thermal conductivity [8].

Ablation performance The evaluation of ablation resistance through oxytorch offers a cost-effective method for swiftly assessing the thermal resistance of materials. This assessment was conducted at The University of Queensland using an oxyacetylene torch calibrated to 5.1MW/m², with a heat flux sensor. The specimen underwent testing for a duration of 1 minute, with results presented in Table 4.

The tested specimen exhibited only minor damage, primarily evidenced by a noticeable color shift from dark green to light green. While SiC derived from polymers generally shows limited thermal resistance at elevated temperatures, the incorporation of pure β -SiC powder significantly improved the specimen's ablation performance. With an ablation rate reported between 40 to 1 mg/s, this result demonstrates the material's robust ablation resistance, which aligns with the literature-reported values [11, 12, 13].



Fig 4. C/SiC specimen before test (left) and after (right)

Table 1. Ablation performance of C/SiC made via PIP

C/SiC	Mass ablation rate mg/s	Mass loss %
Oxytorch	1.248	0.811

Mechanical testing The thermo-structural simulation predicted a maximum stress of approximately 70MPa. Consequently, flat plate panels were fabricated with 14 PIP cycles and subjected to a three-point bending test, as evidenced by the results presented below.

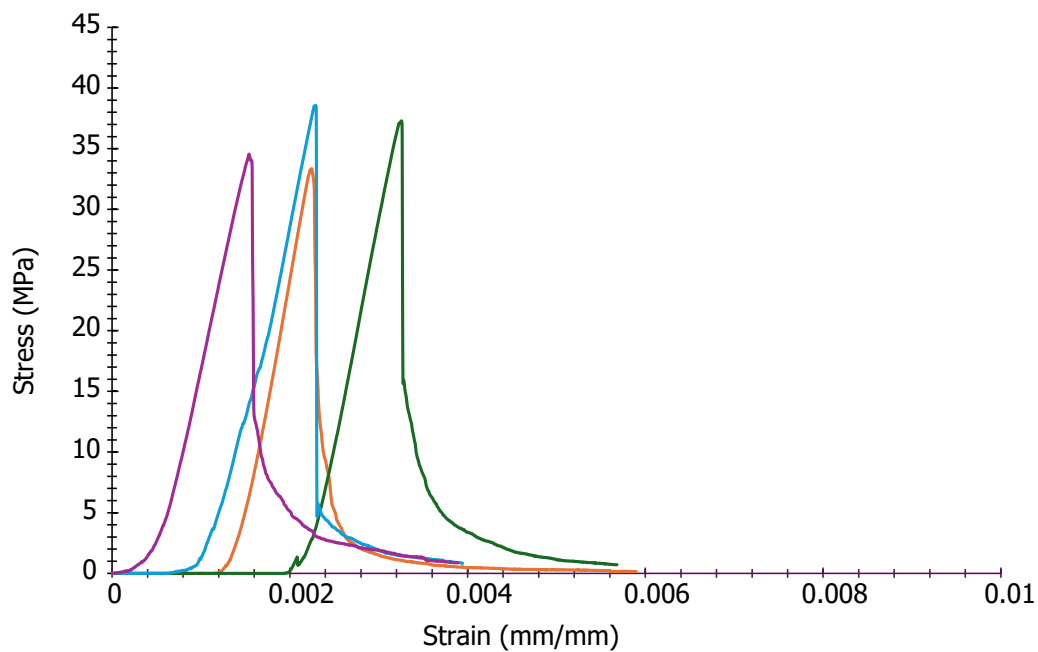


Fig 5. Mechanical testing PIP

The mechanical test results were surprisingly low, with the maximum bending stress only reaching around 35 MPa and resulting in a brittle failure. This might be explained by the lack of interphase coating between the fibers and the matrix. Furthermore, the high number of infiltration cycles might have led the silicon atoms to migrate from the matrix to the fiber, leading to a strong interphase bonding.

Zunjarro et al. investigated the mechanical properties of SiC derived through various heat treatments temperatures and observed such behavior[14]. Yan et al also observed reduced mechanical properties when processed at high temperatures, which aligns with the findings of this test [15]. This phenomenon is thought to be attributed to the Hall-Petch effect, which suggests that increasing grain size negatively affect the mechanical properties. Hence, high-temperature heat treatment results in larger grain sizes, consequently leading to lower mechanical properties.

Table 2. Mechanical properties of C/C-SiC made via PIP

	Flexural strength MPa	Modulus GPa
C/SiC	31.76 $\pm$ 8.58	31.49 $\pm$ 7.15

Overall, to enhance thermal conductivity, C/SiC composites underwent a high number of PIP cycles with varying heat treatments up to 1700C. Although the thermal and ablation performance were satisfactory, this was achieved at the expense of mechanical properties. Furthermore, this method was found to be labor-intensive and resulted in an excessive turnaround time. Consequently, it was decided to transition to the reactive melt infiltration pathway.

2.0.3. Reactive Melt infiltration method

The reactive melt infiltration pathway produces ceramic matrix composites through the reaction between the carbon matrix and molten refractory. This method offers a cost-effective alternative (provided a graphite furnace is available) and is faster than the Chemical Vapor Infiltration (CVI) or PIP process. Unlike the PIP method, the production of C/C-SiC does not necessarily require the application of an interphase on the fiber through CVI. Instead, the fiber protection and weak-fiber interface can be provided through multiple infiltrations of the C/C composite with carbon-forming resin.

To ensure a high thermal conductivity, pitch fibers were used in place of PAN-based fibers, while the carbon matrix was derived from cyanate ester resin. Flat plate materials used for characterization were pyrolysed at 1000C, followed by a re-infiltration with cyanate ester resin. Subsequently, further pyrolysis at 2000C was conducted, and the resulting material was then siliconized at 1600C under vacuum.

Thermal conductivity The thermal conductivity of C/C-SiC was measured by the TA Instruments application laboratory in New Castle, USA, using a DLF-2800. Due to the presence of residual free silicon in the specimen, the maximum testing temperature was limited to 1300°C. The results are presented in Figure 6.

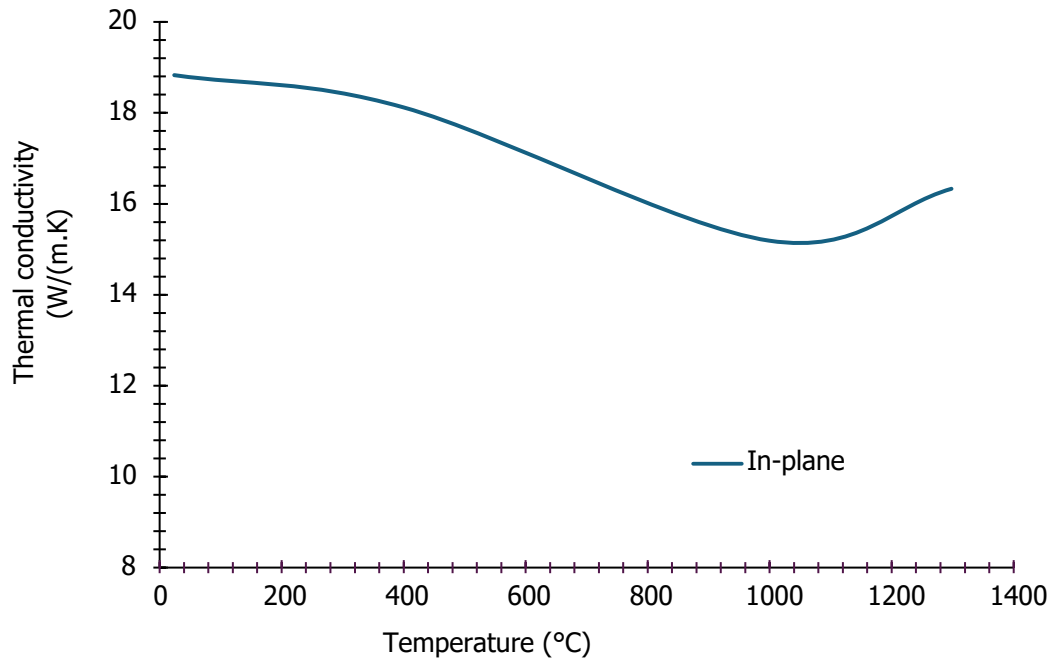


Fig 6. Thermal conductivity LSI

Across the entire measurement range, the thermal conductivity of C/C–SiC was consistently higher than that of C/SiC. Several factors may account for this improvement. First, the use of pitch-based fibers instead of conventional PAN-derived carbon fibers likely contributed, as pitch fibers are well known for their higher intrinsic thermal conductivity. Second, the relatively low porosity (below 5 vol.%) facilitates phonon transport and thus enhances heat conduction.

Ablation performance Similarly to C/SiC, C/C–SiC were tested on the oxyacetylene torch at 5.1 MW/m^2 for one minute, as shown below.

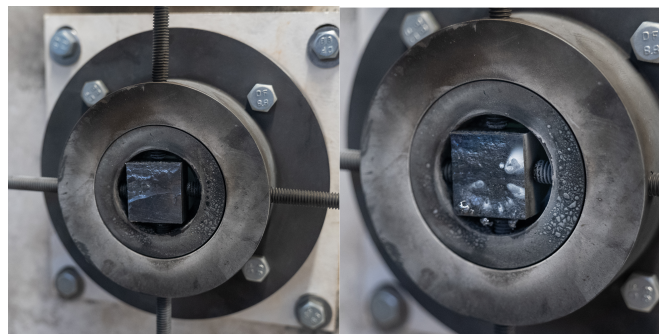


Fig 7. C/C–SiC specimens before (left) and after (right) oxytorch

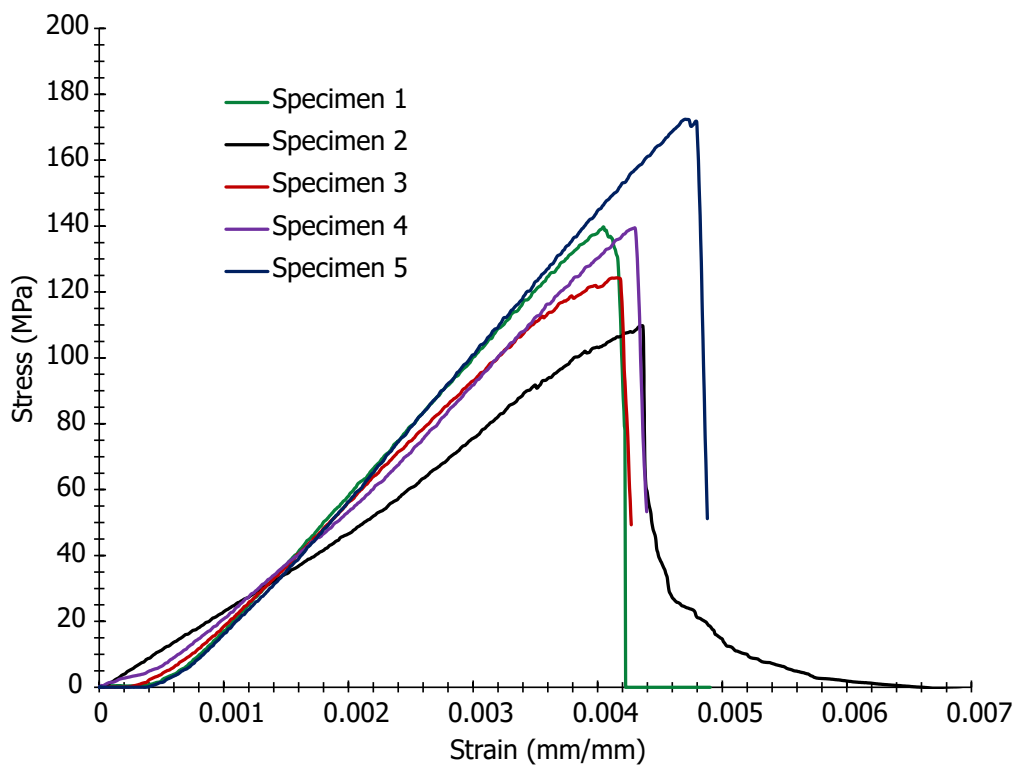
The C/C–SiC composite showed a slight improvement in ablation performance over C/SiC made with the PIP method. This is due to the presence of free silicon on its surface, which was intentionally left to absorb heat. This silicon melted, oxidized, and was then expelled by the gas flow. The resulting white deposit on the surface indicates the formation of silicon dioxide (SiO_2).

Table 3. Ablation performance of C/C-SiC made via LSI

C/C-SiC	Mass ablation rate mg/s	Mass loss %
Oxytorch	0.290	0.139

Overall, the ablation test was deemed satisfactory for the project and comparable to the literature [13].

Mechanical testing Similarly to C/SiC composites, C/C-SiC plates were made and subjected to a 3 point bending test with a span/thickness ratio of 10, with results shown below.


Fig 8. Mechanical test of C/C-SiC composites

The mechanical properties of C/C-SiC exhibited superior flexural strength compared to their C/SiC counterparts produced using the PIP method. The specimens exhibited brittle failure, underscoring the necessity of conducting further re-infiltration of the C/C to enhance the protection of carbon bundles. The obtained values are in line with reported values from the literature. [13, 16].

Table 4. Mechanical properties of C/C-SiC made via LSI

	Flexural strength MPa	Modulus GPa
C/C-SiC	137.15 ±23.30	33.21±6.77

This development paved the way for the subsequent phase, which involved the fabrication and mechanical testing of a scramjet inlet insert prototype using an Instron machine. The strain experienced by the inlet insert was meticulously recorded using a 3D optical camera, while it was subjected to compression, simulating the stresses encountered during flight.

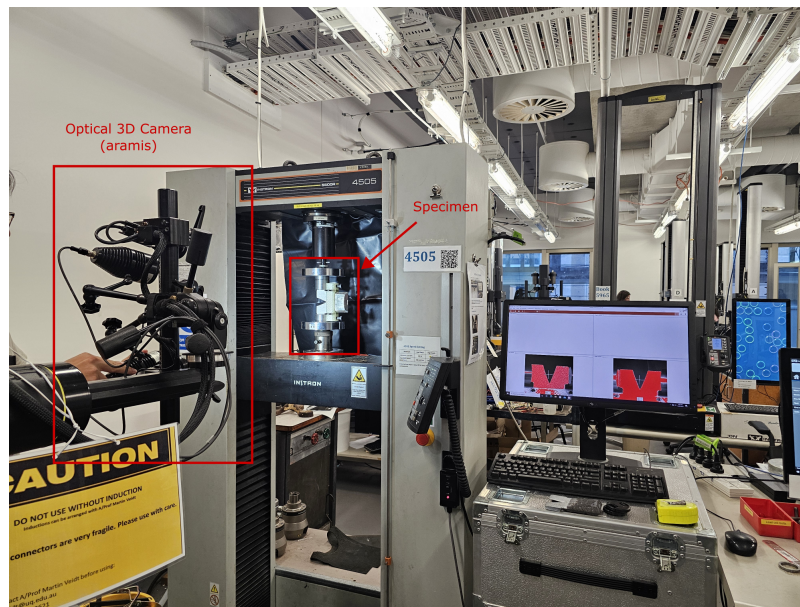


Fig 9. Mechanical test of the scramjet inlet insert

The prototype was subjected to a 500N load three times and up to 900N once, with a displacement of 0.05mm/min, under an Instron Testing Machine. The results are presented in Figure 10.

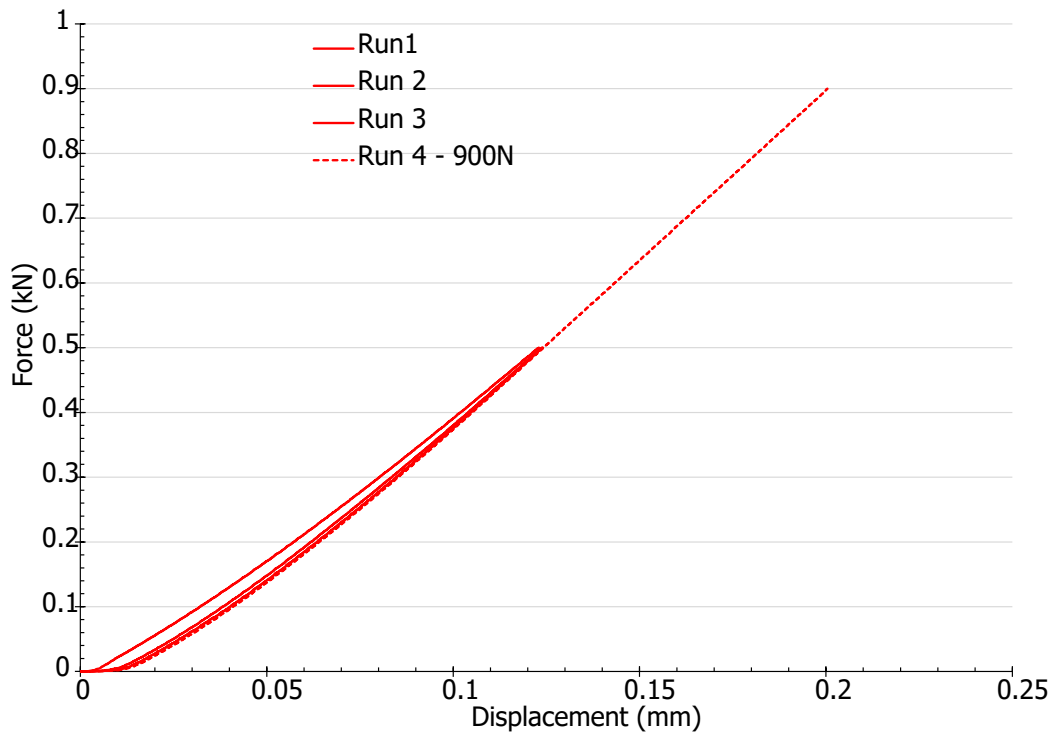


Fig 10. Mechanical cycle test of scramjet inlet insert

The prototype successfully withstood the 500 N compression test, simulating the stresses expected during flight. The modulus remained unchanged over three cycles, indicating the absence of structural damage and confirming that the material response was confined to the elastic region. The load was then increased to 900 N within a 1000 N test cell, again without any failure and with a constant modulus. These results provide strong confidence in the component's mechanical strength and its ability to meet the demands of flight.

2.0.4. Conclusion

The PIP process stands out as the most accessible due to its absence of costly facilities. In the pursuit of developing a material with enhanced thermal conductivity, it was discovered that while the increased number of PIP cycles facilitated the fulfillment of thermal and ablation requirements, they adversely affected the mechanical properties. Consequently, this resulted in a labor-intensive manufacturing process that is impractical for large-scale production. In contrast, the production of C/C-SiC through liquid silicon infiltration was demonstrated to be not only a time-efficient method but also yielded a material with superior performance.



Fig 11. scramjet inlet insert fitted in 3D printed Inconel engine

A robust manufacturing process was demonstrated by the successful production of several scramjet inlet insert prototypes. These prototypes were all test fitted into the 3D-printed Inconel engine, as illustrated in Figure 11.

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