

# High-temperature robotic gripper with ceramic insulation for additive manufacturing

Ayush Kumar Agrawal & Jayendra Kumar\*

Department of Electronics and Communication Engineering, National Institute of Technology Jamshedpur 831 014, India

Received: 18 October 2024; accepted: 02 February 2025

Traditional robotic grippers designed for collaborative robots have often been constrained to specific part geometries or low-temperature operations, creating a need for more adaptable solutions. A high-temperature gripper has been developed with fingers made from alloy steel 4140 and an aluminium oxide ceramic insulator to support automation during post-processing in metal additive manufacturing (AM). Mechanical and thermal characterization tests have been performed to validate the insulator's performance under extreme conditions. Thermal simulations have indicated a temperature difference of 767.58 °C across the insulator when subjected to a 1000 °C steel plate, confirming its role as an effective thermal barrier. The gripper has been designed to withstand temperatures up to 1000 °C and integrated with thermocouples for continuous temperature monitoring during manipulation. This advancement has enabled safe handling of heated components, reduced risks to human operators, and supported greater automation in high-temperature environments, thereby improving safety and productivity in demanding industrial settings.

**Keywords:** Additive manufacturing, Ceramic insulator, Collaborative robots, High-temperature gripper, Internet of things

## 1 Introduction

The demand for high-temperature-resistant robotic grippers has grown urgent with the advancement of industries such as metal additive manufacturing. Additive manufacturing processes, especially laser bed powder fusion, see temperatures well over 1000°C—a level where conventional robotic technology is challenged. While AM has transformed production processes by greatly increasing speed and enhancing accuracy, much of its post-processing tasks—smoothing layer lines, performing heat treatments, and eliminating supports—are done manually. Such reliance on manual labor reduces efficiency dividends from production and puts workers in contact with very high levels of temperature. Most of the robotic grippers now existing, particularly those for COBOTS, are unsuitable for such working conditions<sup>1,2</sup>. Typically, these grippers can take temperatures up to 40-50°C, which is well below the temperatures encountered in post-processing of AM metals. Beginning with efforts to extend their functionality through the use of Kevlar coatings, for instance, offers some improvement, enabling grippers to handle up to 150°C. However, Kevlar starts degrading at about 400°C, again well below the requirement for

high-temperature applications such as in AM. Also, classic high-temperature grippers capable of withstanding extremely high temperatures in forging and hot stamping are usually big and heavy to be fitted on lightweight and adaptable collaborative robots used in modern manufacturing environments.

As far as other forms of gripper design are concerned, it is the Fin Ray-style adaptive gripper that seems to be another one because of its handling flexibility for complicated shapes at a temperature as high as 1200°C. However, this design has limited practical implementation in high-temperature environments due to the melting of the rubber coating on the fingers under extreme heat conditions<sup>3</sup>. It is also said that it confines its use to low or moderate temperature activities, hence making a huge gap in the market for robotic grippers capable of functioning in the demanding post-processing environments of metal additive manufacturing. To this end, the study proposes a new design for such a gripper with active thermal insulation using a conventional end-effector that is suitable for high-temperature applications. To that end, fabrication of the gripper was done by using a 4140 alloy steel finger assembly together with a castable aluminum oxide ceramic insulator. The mechanical strength of 4140 steel is required to handle the metal parts in post-processing. The ceramic insulator acts as a thermal barrier, protecting the steel

\*Corresponding author (E-mail: jkumar.ece@nitjsr.ac.in)

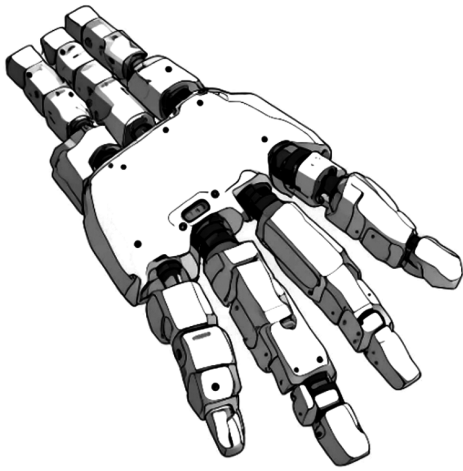


Fig. 1 — Robotic gripper design for high-temperature applications using software.

components from intense heat. It has been noted that aluminum oxide is highly resistant to temperature and can bear more than  $1000^{\circ}\text{C}$  of temperature, by which this material is perfect for the purpose<sup>4,5</sup>. Figure 1 shows the design of the proposed gripper with a 4140 alloy steel finger and a ceramic insulator.

In order to ensure this new design was going to be effective, an extensive series of thermal simulations and mechanical tests were performed. ANSYS Workbench was used for thermal simulations in conditions that commonly face the parts during post-processing of AM—namely, when the temperature of the metal parts exceeds  $1000^{\circ}\text{C}$ . These simulations looked at different thicknesses of the ceramic insulator in order to identify another trade-off between protection from heat and the weight that this novel design would offer<sup>3,6</sup>. A 17 mm thick insulator proved the most efficient, keeping the temperature of the steel finger at a safe  $135.91^{\circ}\text{C}$ , while protecting the lightweight design for utilization with collaborative robots. This balance needs to be struck between thermal protection and mechanical performance so that the gripper is able to work efficiently without an effect on mobility or payload capacity.

Besides the thermal simulations, some mechanical testing, like compression and three-point bending tests, was conducted on the ceramic material to understand its durability under load. The ultimate compressive strength of fully heat-treated ceramic samples was 45.47 MPa, which far exceeded that specified by the manufacturer. These tests thus proved that an insulator of this design would be able to withstand the mechanical requirements during handling of heavy AM parts with excellent thermal protection.

## 2 Materials and Methods

Further validation tests of gripper performance included thermal shock and thermal conductivity measurements. The thermal shock tests were an assessment of the insulator's capability to withstand sudden changes in temperature, a frequent occurrence in AM post-processing when components are transferred from one stage of the process to another<sup>4</sup>. In these tests, ceramic insulators were exposed to a  $1000^{\circ}\text{C}$  steel plate and afterwards showed minimal damage when cooled down, indicating substantial resistance to sudden thermal stress. Also, by CT and scan, there was minimal microcracking proximal to the pores created by the casting process; this is yet again of little consequence since the cracks do not propagate significantly enough to compromise the structural integrity of the ceramic during operation. Indeed, thermal conductivity tests conducted showed that the experimental thermal conductivity of the ceramic was  $5.123\text{ W/mK}$ , which was higher than the specifications given by the manufacturer; it still provides sufficient insulation to prevent excessive heat exposure on the steel components of the gripper. Higher thermal conductivity could be due to differences in material properties or test setup conditions, but in any case, the ceramic showed effective restriction on heat transfer. This was a combined thermal and mechanical test, proving that the gripper design being proposed for handling high-temperature metal AM parts is indeed viable. By incorporating this advanced ceramic insulator with a robust steel finger assembly, the gripper can safely and effectively automate tasks in post-processing, reduce reliance on manual labor, and improve both safety and productivity in an additive manufacturing workflow<sup>7,8</sup>. Previously the human collaborative humanoid robotic hand controlled using sensors where the data is been transferred using IoT was designed and then the several materials are taken which lead to control the humanoid COBOT in the high temperature application as shown in Fig. 2.

The methodology that will be employed in the present study includes a broad set of procedures that will be used for the optimal design of ceramic insulation for high-temperature applications<sup>9</sup>. These include transient thermal simulations, ceramic casting, mechanical testing (compression and three-point bending), and thermal performance studies such as thermal conductivity and thermal shock resistance. This means every step of the methodology was



Fig. 2 — Designed human collaborative humanoid robotic hand controlled using sensors.

undertaken to ensure that the ceramic insulator utilized in the gripper minimizes heat transfer, keeping mechanical integrity due to high stress and thermal conditions associated with the application<sup>10,11</sup>. Thermal simulations have been performed using ANSYS Workbench, in order to assess the facility of heat transfer through the ceramic insulator. In the present case, the transient thermal simulation was selected to capture the time-dependent interaction of heat transfer mechanisms between the ceramic insulator and the 4140 alloy steel plate, which in turn was modeled in simulating the finger assembly of the gripper. Geometrical dimensions of the steel plate were considered to be of length 100 mm × 75 mm × 6 mm, and it was heated up to 1000°C to simulate the conditions encountered during the metal additive manufacturing processes. The initial temperature of the ceramic insulator is taken to be at ambient temperature, 22°C. A frictional contact model simulated the interface between the steel plate and ceramic in such a manner that the heat transfer between the two interacting materials was included within the simulation work. Free-air convection has been applied with a heat transfer coefficient of 5 W/m<sup>2</sup>K for simulating natural cooling after the heating phase. It is assumed that the ambient temperature is the same as inside the furnace and starts heating up to 1000°C before air cooling back from 600°C after a minute, over real cooling scenarios<sup>12,13</sup>. The simulation time in total is 60s. However, the dataset was collected every 1 second to

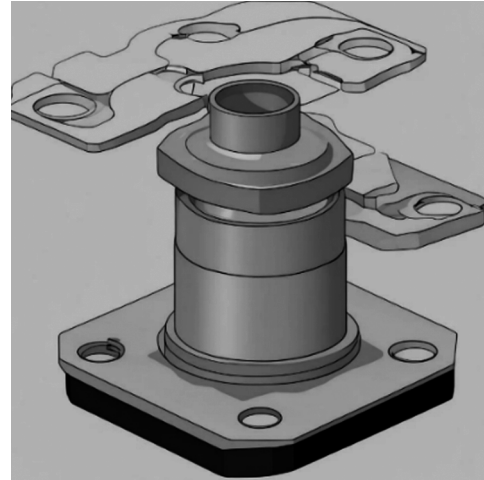


Fig. 3 — Microcrack formation in ceramic insulators.

indicate how the temperature changes dynamically with time. These tests simulated a range of ceramic insulator thicknesses—7, 12, 17, 22, and 27 mm—to determine an optimal thickness with which enough thermal insulation would be provided without over-increasing the gripper weight<sup>14</sup>. In each simulation, maximum and minimum temperatures across the insulator were recorded. A small Python script visualized the temperature gradients across the ceramic insulator block. Material properties of the ceramic, such as thermal conductivity and coefficient of thermal expansion provided by the manufacturer were included in the simulation<sup>15,16</sup>. The most important objective of the simulation is to find an optimal thickness that minimizes the heat transferred from the steel plate to the gripper's steel finger without losing the structural strength and functionality of the gripper<sup>17</sup>.

To fabricate the ceramic insulator for the gripper, Al<sub>2</sub>O<sub>3</sub> ceramic was cast in a purpose-built mold. The mold was 3D-printed out of PETG, which provided sufficient dimensional accuracy and possessed adequate durability for multiple uses<sup>18,19</sup>. A mold-release spray was used inside the mold for easy removal of the ceramic after curing. Because it is anticipated that the ceramics in general will shrink during curing, the mold was designed to be 2% larger than the insulator's final dimensions to accommodate this shrinkage. Figure 3 shows the microcracks of the ceramic insulator formed during casting taken by CT scans. Casting pins were inserted into the mold in order to create the needed attachment points for the insulator in the gripper assembly.

The mixture consisted of aluminum oxide powder with an activator at a weight ratio of 100:25. The activator provided bonds for the aluminum oxide particles and activated the curing mechanism. The prepared mixture was carefully poured into the mold in such a way that it was evenly distributed within the cavity. Following a 20-minute settling period, excess material was wiped off the surface of the mold and the ceramic was allowed to cure at ambient temperature for 16-24 hours. After the initial curing stage, the ceramic was carefully removed using a blade to avoid fracturing fragile material. Two stages of post-curing were used as a method of improving mechanical and thermal properties of the ceramics. It was followed by the first post-curing heating cycle of the ceramic to 110°C for 2.5 hours, which removed the residual moisture from it and gave substantial hardening of the material. The second post-curing step consisted of heating the ceramic to 1000°C in two hours while ramping the temperature at 100°C/hour to avoid thermal shock. These post-curing processes played a critical role in making the ceramics suitable for high-temperature application due to the fact that they enhanced structural integrity considerably.

In this regard, six samples were tested for mechanical properties through compression and three-point bending tests and had been fabricated by means of the aforementioned casting process. Three specimens were incompletely treated with heat; the treatment included only the first stage of post-curing at 110°C. The rest of the three were completely heat-treated through both stages of post-curing up to 1000°C. All the specimens were measured with calipers to standardize their dimensions as per test specimens before mechanical testing. In Table 1 the thermal and mechanical properties of materials used in robotic grippers are discussed. It points out that alloy steel 4140 and aluminum oxide ceramic in the proposed gripper are the materials that provide high compressive strength with resistance to temperature; thus, it is suitable for extreme temperature applications with advantages over alternative materials such as Kevlar and rubber-coated grippers.

Compression tests were carried out by using the MTS Insight 30 testing machine and equipped with a 3 kN force sensor. Compressive force was applied to the test specimens using this equipment, which recorded data on load, extension, stress, and strain in real time. The plotting of the stress-strain curves for each specimen was carried out in order to examine its behavior under compressive loads and to obtain the ultimate compressive strength. These tests provided important information about the capability of the ceramic to endure high forces in compression, which is basically essential for performance in a high-temperature gripper environment.

Next, three-point bending tests were performed to measure the flexural strength of the ceramic insulators, where a central force was applied by a bending chuck to the specimens while supporting them at two points. The recording and analysis of data were kept identical to the compression tests while performing the bending tests: stress-strain curves were generated in order to test the strength in bending and elasticity of the ceramic. The Python scripts were used in processing both compression and bending test results in order to visualize the mechanical performance difference among partially and fully heat-treated specimens. These fully heat-treated ceramics would, therefore, be expected to realize better strength from their high density and structural integrity due to the post-curing that was done at a very high temperature.

In further determining the thermal performance of the ceramic insulation, a test on thermal conductivity was performed on a cylindrical ceramic specimen. This test specimen measured about 106.5 mm in diameter and 4 mm thick, fabricated by the same ceramic casting method<sup>20</sup>. In all, eight points along two perpendicular centerlines and a 20 mm radius circle fitted with thermocouples on both faces of the specimen. The ceramic specimen was placed on top of a hot plate; aluminum and polymer reference disks were used for comparison in thermal conductivity. The entire setup was covered with foam for insulation and topped with a beaker full of de-ionized ice to create a controlled atmosphere. The hot plate was then

Table 1 — Thermal and mechanical properties of materials used for high-temperature grippers.

Material	Ultimate compressive strength (MPa)	Thermal conductivity (W/mK)	Max operating temperature (°C)	Weight (kg)
4140 alloy steel	600-700	42	1000	Medium
Aluminium oxide ceramic	45.47	5.123	1000+	Low
Kevlar coated gripper	20-25	0.04	150	Low
Fin ray gripper (Rubber Coated)	~5	0.15	120	Low

set to 1000°C. Already at a state of equilibrium, temperature data from the setup were recorded, via an NI-9213 Temperature Input Module interfaced to LabVIEW, at every minute interval<sup>21</sup>. Data processing was done in Excel, and the average values of the thermocouples' readings on the aluminum and polymer discs were applied in computing the thermal conductivity using Fourier's law of heat conduction for the ceramic material. This test was done to confirm the capability of the ceramic in retarding the transfer of heat and that it should protect the gripper's steel components from excessive heat exposure.

Lastly, thermal shock tests were conducted to determine resistance among these ceramics to sudden changes in temperature. Such thermal shock was conducted by placing three ceramic insulators that had complete heat treatment on top of a heated steel plate at a temperature of 1000°C. Visual examinations took place for every 2 min, 5 min, 10 min, 30 min, and 1 h to observe any change in the ceramic, such as cracks or discoloration. After the steel plate had cooled down, the ceramic insulators were tested for their structures again after a cooling period of 10 hours. The test was purposed to simulate sudden temperature fluctuations that the gripper may undergo during an actual operation and whether the ceramic could keep up with such performance.

### 3 Results and Discussion

This final gripper design included one finger made from 4140 alloy steel, together with a ceramic insulator that was optimized for high-temperature applications such as those encountered in metal

additive manufacturing. This ceramic insulator is critical in reducing the heat transfer from the hot workpiece into the gripper, thus preventing excessive thermal energy from reaching the steel parts. To accomplish this, the width and thickness of the insulator were determined in great detail, with the final design settling on a 17 mm thick piece of ceramic. This was obtained after thermal simulations, which returned the best compromise between reduced heat transfer and maintaining functionality of the gripper without adding mass that was not needed. The insulator was attached to the gripper using shoulder bolts—a method of attachment that makes for easy and secure fastening without over-tightening into the delicate ceramic. Figure 4 displays thermal simulations showing the temperature distribution in the ceramic insulator at various thicknesses. A thermocouple was also mounted in the gripper to provide real-time temperature monitoring, allowing safe handling up to 1000°C. Compressive stress-strain curves of partially treated versus fully treated ceramic samples. The design preserved the mechanical function of the gripper while it improved the overall thermal resistance significantly for high-temperature applications as shown in Fig.5.

Thermal simulations performed using ANSYS software were key to refining the design, as they allowed for the evaluation of different insulator thicknesses and their effects on the heat transfer. Five different ceramic thicknesses were tested, with a 17 mm insulator emerging as the optimal choice. The simulations revealed that this thickness reduced the temperature on the gripper's steel finger

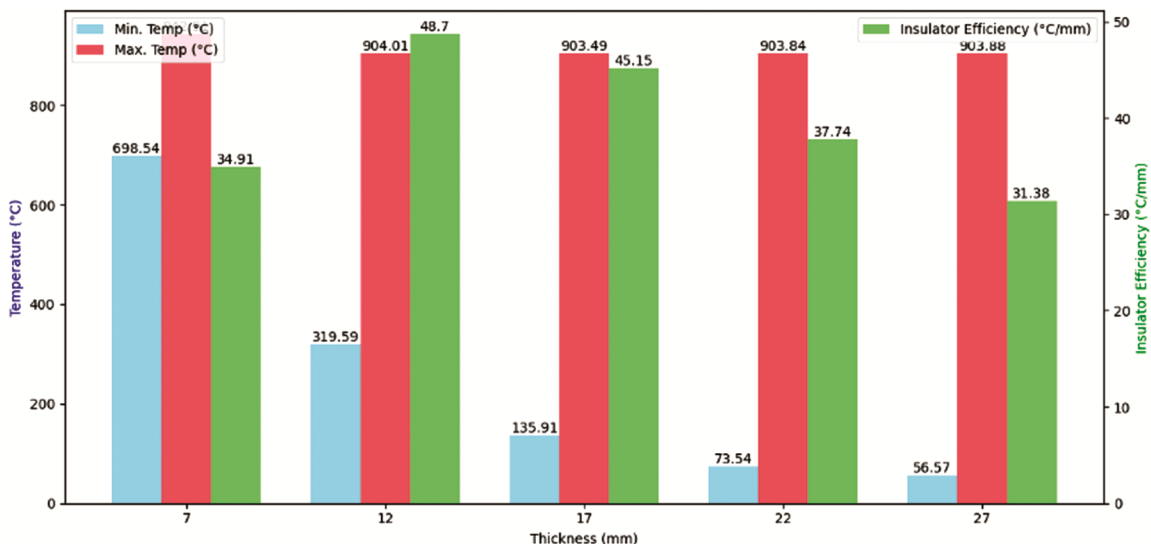


Fig. 4 — Thermal simulation results: Temperature distribution across ceramic insulator thicknesses.

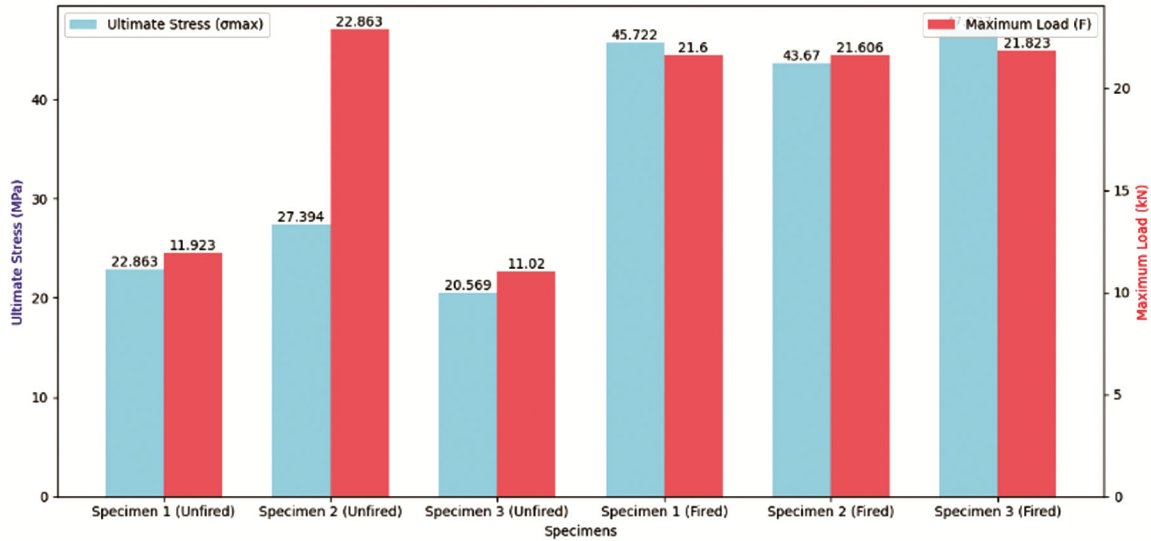


Fig. 5 — Stress-strain curves: Compression tests of partially and fully heat-treated ceramic samples.

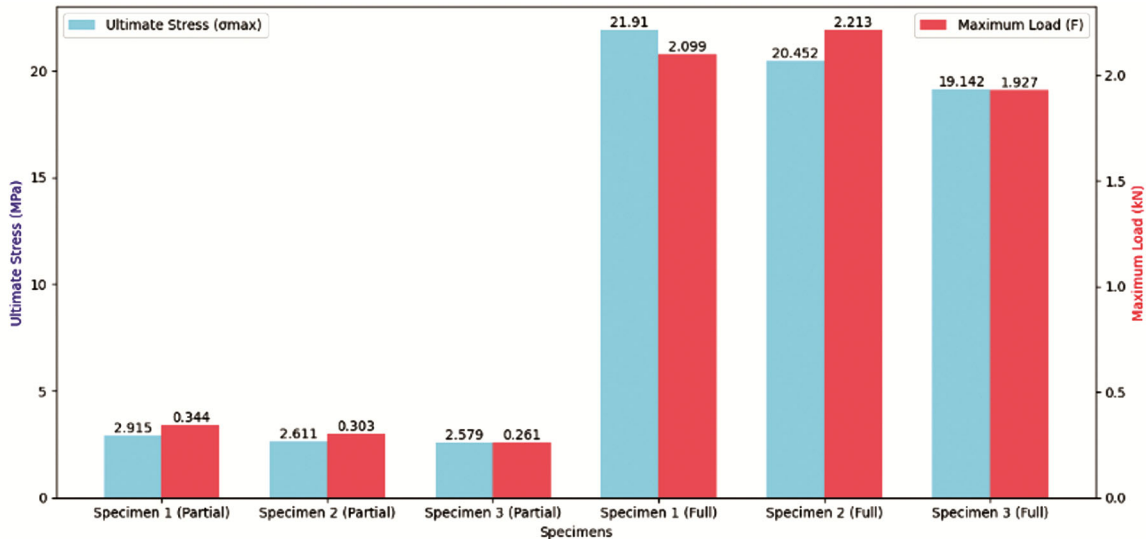


Fig. 6 — Stress-strain curves: Three-point bending tests of partially and fully heat-treated ceramic samples.

to 135.91°C, well below the critical limits, allowing the gripper to operate safely in extremely high-temperature environments. Figure 6 shows the results of three-point bending tests for partially and fully heat-treated ceramic samples, indicating their bending strength. While thicker insulators could provide even greater thermal resistance, they introduced diminishing returns in terms of heat reduction while significantly increasing the gripper's weight, which would compromise its performance. The design needed to balance thermal protection with the mechanical functionality of the gripper, and the 17 mm insulator offered the best compromise. Figure 7 illustrates the setup used for testing the

thermal conductivity of the ceramic insulator and presents the measured data. Additionally, the simulations highlighted the effectiveness of the ceramic in limiting heat transfer, making it suitable for prolonged use in high-temperature environments, such as those found in metal manufacturing.

Extensive mechanical testing was conducted to validate the suitability of the ceramic material for the gripper design. Compression tests revealed a marked difference between fully heat-treated and partially heat-treated ceramic samples, with fully treated ceramics achieving an ultimate stress of 45.47 MPa, nearly double the 23.61 MPa of partially treated samples. The fully treated ceramics exhibited brittle

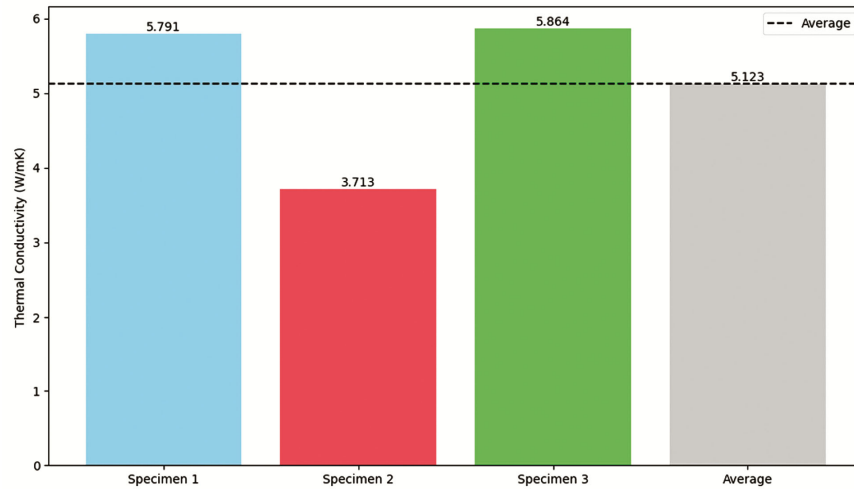


Fig. 7 — Thermal conductivity test set up and results.

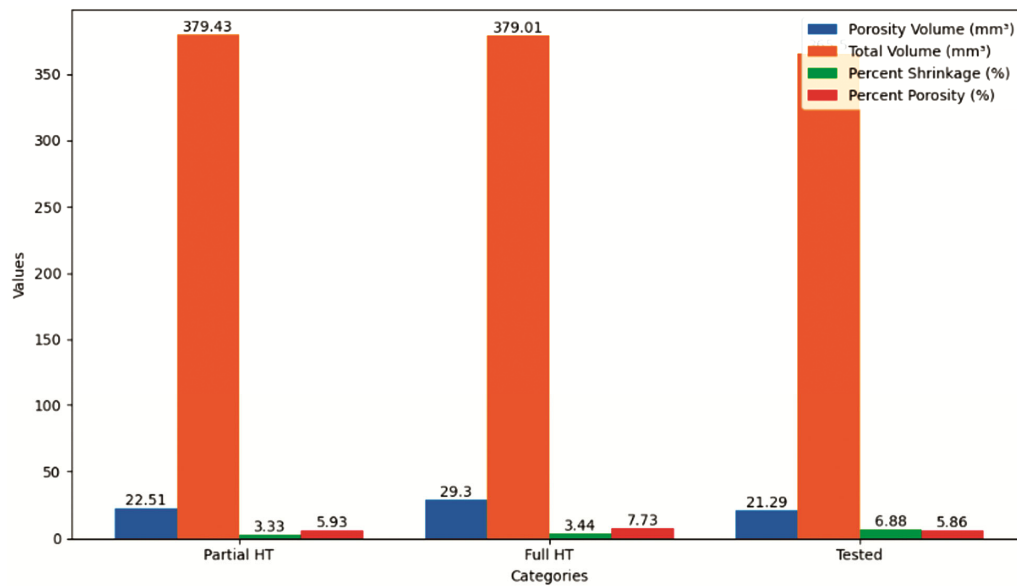


Fig. 8 — Computed tomography (CT) scan porosity results.

failure at the ultimate stress point, whereas partially treated samples exhibited a more ductile failure mode. Figure 8 shows porosity detected in the ceramic samples through computed tomography (CT) scans, highlighting potential structural weaknesses.

The results indeed confirmed that the fully heat-treated ceramic had a strengthened material, more applicable to high-load, high-temperature applications. The results were further supported through three-point bending tests, in which the ultimate stress had a mean of 20.50 MPa for fully treated ceramics, as opposed to just 2.70 MPa for their partially treated counterparts. Notwithstanding their inherent brittleness, the fully treated ceramics

performed well and indicated an ability to sustain mechanical stresses related to gripper use.

Besides the mechanical tests, thermal conductivity and thermal shock tests were also performed. The thermal conductivity of the ceramic was 5.123 W/mK. This value outperformed the 1.44 W/mK pointed out by the manufacturing company, while still providing good insulation. Thermal shock tests also demonstrated that the ceramic material was resistant to sudden changes in temperature without significant deterioration in structure, thus proving it was tough enough for service under high-temperature conditions. CT scans showed microcracks located around pores in the

ceramic, more due to casting than thermal stress. These cracks did not show much growth during service, confirming the reliability of the material against thermal and mechanical stresses.

#### 4 Conclusion

The paper presents a design for automating the post-processing in additive manufacturing with the help of collaborative robots. Simulation and experimental procedures for the testing of the cast ceramic insulator recorded a compressive strength of 45.57 MPa and modulus of rupture of 20.50 MPa. Thermal conductivity obtained was 5.123 W/mK, higher than the specified value, yet effective. While performing object manipulations, simulations confirmed that the gripper would not be damaged even in temperatures up to 1000°C. There was thermal stress in the pores due to inaccuracies in casting. The insulator was promising to last for more than one cycle. Since both the withstanding temperature and grip performance were tested independently, promising results were obtained. Thus, a design suitable for starting the replacement of low-temperature grippers in high-temperature conditions was found. The versatility of the casting process allows the fabrication of custom shapes beyond the standard rectangular design.

#### References

- 1 Patel R & Singh T, *J Therm Anal Calorim*, 146 (2021) 1205.
- 2 Zhang L & Chen Y, *Surf Coat Technol*, 429 (2022) 127927.
- 3 Banerjee A & Das S, *Mater Manuf Process*, 38 (2023) 98.
- 4 Agrawal A K & Kumar J, *J Sci Ind Res*, 83 (2024) 819.
- 5 Clerigues D, Wubben J, Calafate C T, Cano J C & Manzoni P, *EURASIP J Wirel Commun Netw*, (2024) 39.
- 6 Saeed K & Hashim T, *Int J Mater Sci*, 67 (2022) 745.
- 7 Chandra V & Ram M, *J Adv Mater*, 54 (2021) 231.
- 8 Liang Y & Feng S, *Metall Sci Technol*, 59 (2022) 789.
- 9 Nair P & Shah A, *Appl Mater Today*, 45 (2023) 102540.
- 10 Kaur J & Singh A, *Addit Manuf*, 38 (2022) 101748.
- 11 Agrawal A K, Pidge P, Bharti M, Dev M P & Kedare P K, *Advances in Manufacturing and Industrial Engineering: Select Proceedings of ICAPIE 2019*, (Springer, Singapore), ISBN: 978-981-15-5179-0, 2021, p. 975.
- 12 Thayer T C, Vougioukas S, Goldberg K & Carpin S, *IEEE Trans Autom Sci Eng*, 17 (2020) 1184.
- 13 Bose T & Pal R, *Ceram Int*, 49 (2023) 237.
- 14 Gupta M & Arora S, *Int J Heat Mass Transf*, 189 (2022) 122516.
- 15 Nascimento P & Silva M, *Int J Adv Manuf Technol*, 110 (2020) 2545.
- 16 O'Neill K & Smith R, *Robotics*, 12 (2023) 45.
- 17 Lee D & Park J, *IEEE Trans Ind Electron*, 68 (2021) 9812.
- 18 Albani D, IJsselmuide J, Haken R & Trianni V, *Proc 14th IEEE Int Conf Adv Video Signal Based Surveillance (AVSS)*, IEEE, (2017) 1.
- 19 Gazi P, Jamshidi M, Jevtic A & Andina D, *Proc IEEE Int Syst Conf*, IEEE, (2010) 169.
- 20 Zhao F & Wang Q, *Appl Mater Today*, 27 (2022) 101330.
- 21 Kapoor S & Gupta N, *Compos Part B Eng*, 247 (2023) 110502.