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ABSTRACT

Silicon carbide (SiC) is a high-performance ceramic renowned for its excellent strength, thermal stability, and corrosion resistance, making it highly critical for advanced applications. Yet, achieving reliable joints remains challenging, especially given the need for localized heating rather than bulk heating of an entire SiC component. Laser-assisted joining has emerged as a promising alternative, offering the advantages of localized heating, rapid processing without the need for pressure, and precise energy control that significantly minimizes impact on adjacent materials. This study examines the feasibility of using two different infrared diode lasers for pressure-less, localized joining of SiC/SiC tubes to SiC/SiC end-plugs. The results are compared with those obtained using conventional furnaces. A silica-alumina-yttria-based glass is utilized as the joining material. The morphology, microstructure, and mechanical strength of the joints are analyzed, with strength evaluated through push tests designed to detach the end-plug from the tube.

1. Introduction

Continuous SiC fiber reinforced-SiC matrix ceramic composites (SiC/SiC) are highly regarded as interesting materials for both fusion and fission advanced nuclear reactor components, like first walls and blankets, control rods cladding, etc., due to their exceptional strength at high temperature, and resilience to nuclear environment.

Despite extensive research on these materials, their fabrication into large or complex structural components remains a significant challenge.

Several technologies and materials have been proposed for joining of SiC/SiC components for nuclear reactors. Joining of SiC/SiC can be achieved through various methods, including nano-infiltration and transient eutectic (NITE) joining, brazing, diffusion bonding, glass-ceramic joining, polymer-derived SiC joining, and MAX-phase joining [1–5].

Among them, laser-assisted joining seems to give promising results as a pressure-less, localized heating joining technology suitable for SiC/SiC operating in a nuclear (and other) environment [6–10].

A pressure-less, localized heating joining technology for ceramic matrix composites (CMC) is of extreme importance to widen their use. As an example, the sealing of SiC/SiC tubes, which are proposed as an alternative to zirconium-based alloys in Light Water Reactors, would require the heating of the entire 4-meter-long SiC/SiC component to join just a few millimeter long region, close to the end-plug.

The present work reports on preliminary results on laser assisted joining of SiC/SiC tubes to a SiC/SiC end-plug by two different techniques involving diode lasers, both operating in the infrared: one with a maximum power of 3 kW, wavelengths of 808 and 940 nm, available at Technische Universität Dresden, Germany (TUD), and a second one with a maximum power of 4 kW, wavelength 1020–1060 nm, available at J-Tech@PoliTO, Politecnico di Torino, Italy (POLITO).

The selected joining material is a glass-ceramic labeled as SAY: the SAY glass ceramic behavior has been widely studied and this material has been proposed as pressure-less joining material suitable for nuclear applications [4,11–14]; apart from the nuclear field, SAY can be used

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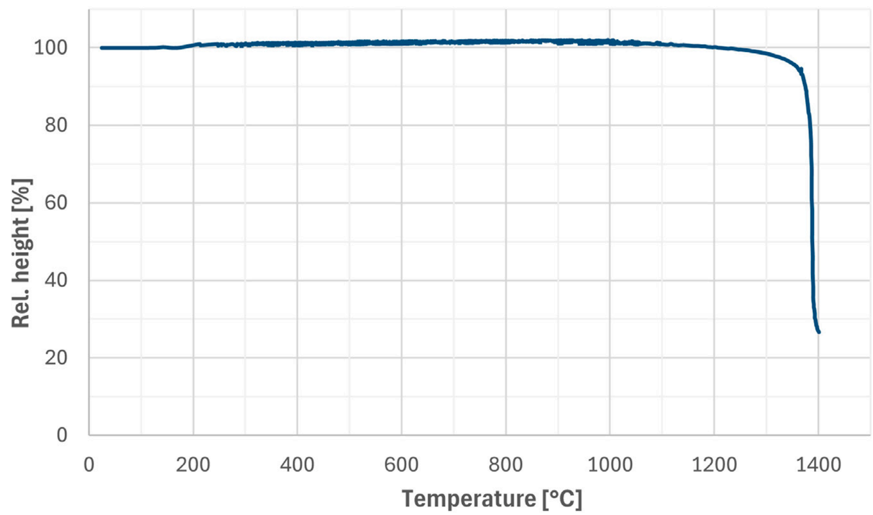

Fig. 1. Relative height % obtained by Hot Stage Microscopy on a SAY glass-ceramic pellet, showing its thermal stability in air up to 1200 °C.

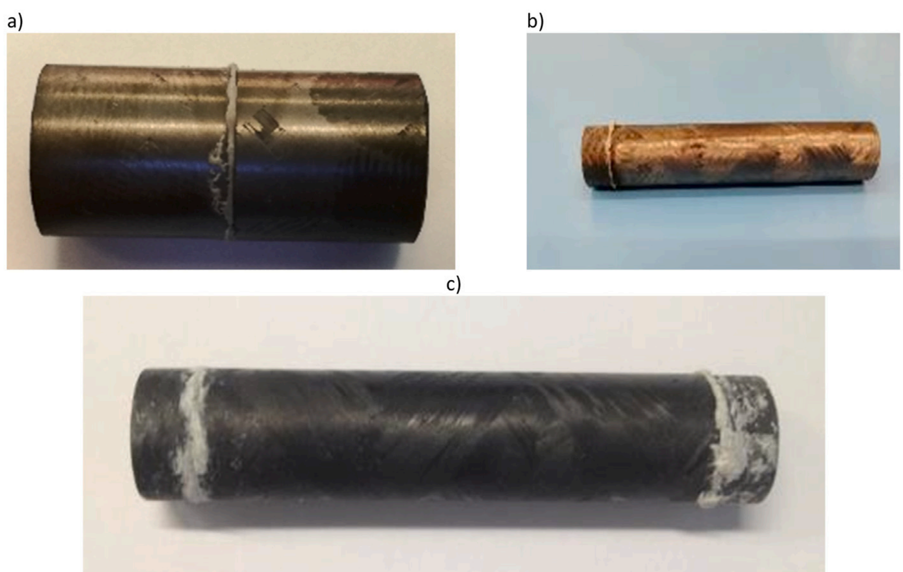

Fig. 2. SiC/SiC tubes joined together (a) and closed by a SiC/SiC end-plug on one side (b) or both sides (c). The joining material is the SAY glass-ceramic. Joining process in a controlled atmosphere furnace under Ar flow.

as a pressure-less joining material for several industrial applications requiring high temperature stability.

Its wettability on SiC is excellent and once crystallized, the three crystalline phases are mullite, cristobalite and keivite ($Y_2Si_2O_7$); no residual amorphous phase was detected and its CTE is close to the SiC/SiC one.

Additionally, SAY has been tested in a neutron environment as joining material for SiC/SiC and it was demonstrated to be almost unaffected in term of bending strength after neutron irradiation at 600 °C, 16.3 x 1024 n/m^2 and at 820 °C, 31–32x 1024 n/m^2. A bending strength of 122 MPa and 118 MPa, before and after neutron irradiation, respectively, was measured and reported.[11]

The SAY glass-ceramic was also subjected to 5.5 MeV 4He+ ion irradiation [14] to investigate the effects of high displacements per atom (dpa) and gaseous product concentration on its microstructure. Despite the statistical limitations of that study, both XRD and microscopical analyses of the irradiated surfaces did not reveal any discernible changes in the microstructure or morphology of the SAY glass-ceramic. Similarly, no significant effects on porosity due to irradiation were observed. TEM cross-section analysis [14] confirmed that SAY glass-ceramic did not undergo amorphization, even in regions where helium implantation resulted in nearly 40 dpa. As expected at high irradiation fluences, SAY exhibited high concentrations of helium bubbles, more evenly distributed within the grains, and also detected outside the implantation layer. Remarkably, despite helium reaching concentrations of approximately 50 atomic percent, only sporadic cracking was observed within the grains in SAY.

Morphology and micro-structure of furnace- *versus* laser-joined SiC/SiC tubes to end-plugs by SAY glass-ceramic will be discussed, together with their mechanical strength, measured by a push method aimed to detach the end-plug from the tube.

2. Experimental

2.1. Materials

The SiC/SiC were provided by Commissariat à l'énergie atomique et aux énergies alternatives, France (CEA): details about their preparation and characteristics can be found in [15].

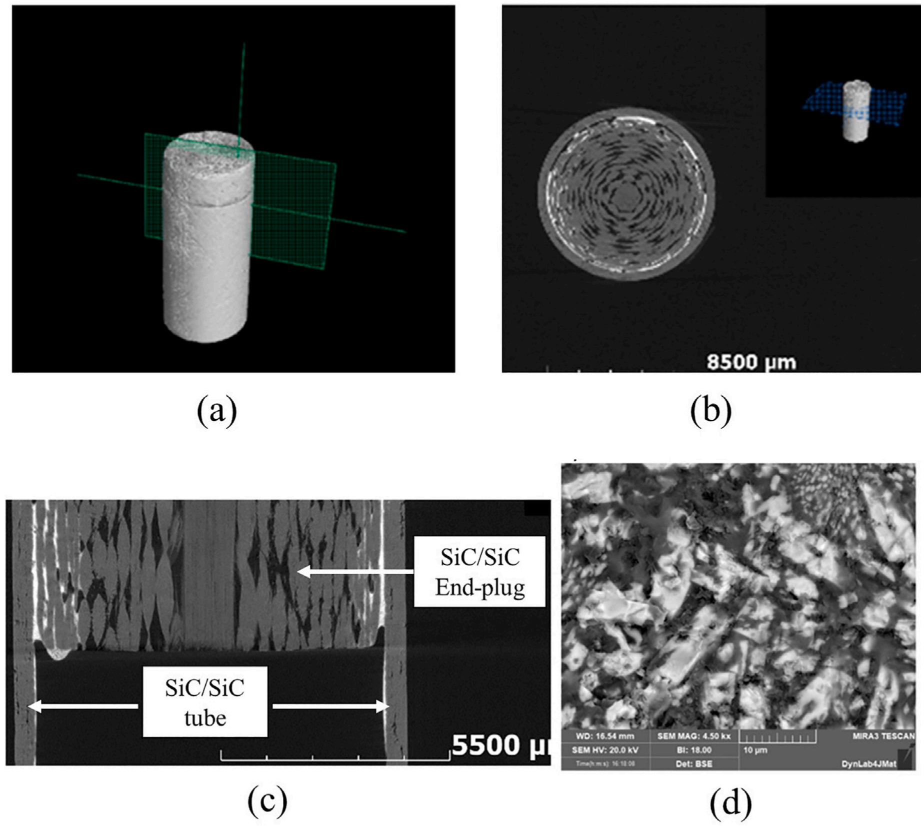

Fig. 3. CT-scan of a SiC/SiC tube closed by an end-plug (a-c): the joining process was done in a controlled atmosphere furnace under Ar flow. The joining material is the SAY glass-ceramic, showing the typical glass-ceramic structure (d).

The tubes' size was 9 mm external diameter, 600-micron thickness, 35 mm length; the end-plugs were prepared by the same process as the tubes.

The joining material selected for this work was a glass labeled "SAY" from its composition, based on SiO_2, Al_2O_3 and Y_2O_3.

SAY glass preparation, characterization and properties, including after neutron and ions irradiation, have been published in [4,11,13,16–18] and briefly summarized here. SAY composition is : SiO_2 54 wt%, Al_2O_3 18.07 wt%, Y_2O_3 27.93 wt%, with a glass transition temperature of 910 °C.

When SAY glass is used as joining material, the joining processes is done at 1375 °C, with a 20 min hold time, heating rate of 1000 °C/h, followed by a crystallization of one hour at 1235 °C. This thermal process gives to the formation of a SAY glass-ceramic characterized by three crystalline phases: cristobalite, mullite and yttrium disilicate ($Y_2Si_2O_7$, keivyite); the coefficient of thermal expansion (CTE) of the glass-ceramic is 5.49 *x* 10-C-1 (measured between 400 °C and 700 °C), without any detectable residual amorphous phase.

The SAY glass was powdered and sieved at less than 38 μm and pressed to obtain a 3 mm diameter, 3 mm high cylinder; the obtained cylinders were heat treated in a tubular furnace in Ar flow with the same thermal treatment used for the joining process (1375 °C, 20 min hold time, heating rate of 1000 °C/h, one hour at 1235 °C) to obtain a SAY glass-ceramic cylinder. The thermal behavior of SAY glass-ceramic cylinders was measured by Heating Stage Microscopy (HSM) (SM, Hesse Instruments, Germany) up to 1400 °C, in air.

The SAY glass-ceramic refractory behavior under load was measured according to [19].

A cylindrical pellet of 8,9 mm diameter, 8,4 mm high, was obtained by pressing the SAY glass powder;the pellet was then heated in a tubular furnace with the same thermal treatment used for the joining process reported above (1375 °C, with a 20 min hold time, heating rate of 1000 °C/h, one hour at 1235 °C) to obtain a glass-ceramic. The SAY glass-ceramic pellet was initially loaded with an applied load of 59 g (corresponding to 10 kPa) and heated at 900 °C (dwell time 1 min, heating rate 5 °C/min), followed by heating at 1250 °C (dwell time 1 h). The same thermal treatment was done on a second pellet, but with a higher applied load of 166 g (corresponding to 26 kPa) then heated at 900 °C (dwell time 1 min, heating rate 5 °C/min) followed by heating at 1250 °C (dwell time 1 h).

In both cases the final height and diameter were measured by a precision caliper and compared to the initial ones.

A slurry made of SAY glass powders mixed with a minimal amount of isopropanol was used as joining material: SiC/SiC tubes and end-plugs were joined by this slurry, initially in a furnace operating in Ar flow (Xerion - XVAC Series) with the same thermal treatment described above, to obtain butt-joints between two tubes, or by closing one or both ends of a tube by end-plugs.

To obtain butt-joints, the slurry was manually applied by a spatula to their annular mating surfaces. In the case of tubes joined to the end-plug, the slurry was applied manually by a spatula all over the end-plug surface, then inserted into the tube. The amount of slurry was measured ex-post by weighting the sample before and after the slurry application. Its amount was kept as constant as possible, considering the manual procedure, for each butt-joint and for each tube closed by end-plugs.

2.2. Joining setup

Two different lasers were used as pressure-less, localized heating sources for the joining of SiC/SiC tubes and end-plugs:

- A diode laser DL 031Q (Rofin-Sinar Laser GmbH, Hamburg, Germany) at (TUD) with a maximum power of 3 kW (wavelength 808 and 940 nm) was used in a continuous mode and coupled with a

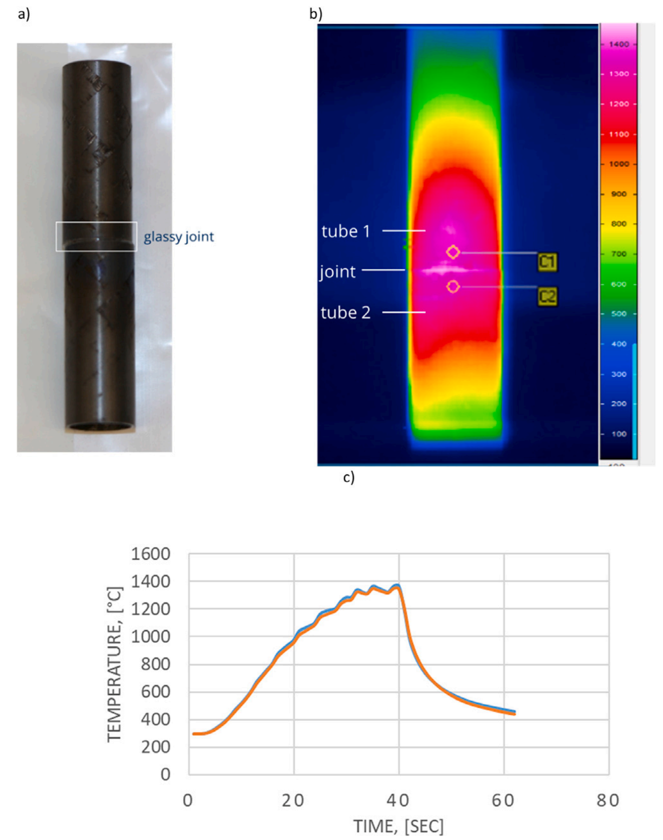

Fig. 4. SAY joined SiC/SiC tube by laser at TUD (Dresden, Germany) (a); temperature distribution on the SiC/SiC tubes after 40 s of laser beam impact (maximum of temperature) (b); temperature measurement during the laser joining process, measured in the laser spot center(c).

scanner. The goal was to achieve very homogeneous heating of the tubes. The laser beam was guided via a scanner (powerSCAN 33, Scanlab GmbH, Puchheim, Germany), allowing the energy distribution during the heating of the test samples. The laser surrounds the cylinder due to the high scanning rate. To heat the SiC/SiC tubes to the temperatures needed for the joining with SAY slurry, the laser power density was increased during 30 s up and held for another 10 s.

- A diode-laser LDF 4000-40 (Laserline, Mülheim-Kärlich, Germany) with a maximum power of 4.4 kW, working with two wavelengths of 1020-1060±10 nm, was used as heating source. The laser head was an OTS-5 (Laserline, Mülheim-Kärlich, DE), mounted on a 6-axis robot IRB 2400 (ABB, Zurich, CH). In this process, the laser directly targeted the localized joining area. During cylinder rotation, the laser followed a ramp-up of 5 s, then remained constant for 35 s.

Both lasers were initially used to melt SAY glass powders on a SiC slab, then to join SiC/SiC tubes and finally SiC/SiC tubes to end-plugs by SAY slurry, in air.

2.3. Joint evaluation

Cross-sections of the joints were investigated by means of Field Emission Scanning Electron Microscopy, equipped with Energy Dispersive Spectroscopy (FESEM-EDS SUPRATM 40, Zeiss and Merlin Gemini Zeiss). The microstructure of polished cross-sections was investigated by electron probe microanalysis (EPMA, JXA-8530F, JEOL Ltd, Japan), equipped with a wavelength dispersive analysis system. The beam current and accelerating voltage were fixed at 50 nA and 15 kV respectively.

Micro-Computed Tomography (micro-CT) inspections are performed using a custom-built setup with a 300 kV X-ray emitter, a minimum focal spot size of 5 μm and a flat panel detector with a resolution of 2048 x 2048 pixels. The distances between the emitter, the sample, and the detector are adjusted to achieve optimal resolution. For specimen analysis, the scanning parameters are carefully optimized, with settings of 140 kV and 60 μA, resulting in a nominal electron beam power of 8.4 W. During acquisition, the distance between the X-ray source and the specimen is maintained at 100 mm, and the distance between the source and the detector is set at 1200 mm, yielding a final resolution of 16 μm per voxel. To enhance image quality, a 0.2 mm copper filter is applied to the X-ray beam to remove low-intensity radiation and reduce noise during the reconstruction phase. The three-dimensional volume of the specimen is reconstructed using the filtered back-projection algorithm in VG MAX 3.5 software (Volume Graphics GmbH, Heidelberg, DE), based on a total of 1600 X-ray projections. In the post-processing phase, the joint region is inspected to detect its overall quality and the presence of cracks and porosity.

Mechanical characterization was carried out both at CEA and POLITO on a universal tensile/compression testing machine using a specifically designed push test in which an axial and uniform compression loading aimed at detaching the end-plug from the tube is applied on the inner face of the end-plug until failure. Tests done at CEA are also equipped with an Acoustic Emission.

The test specimen, consisting of the tube joined with the end plug is secured into a specifically designed holder that is placed in the testing machine: the compression force on the end plug is applied thanks to a loading rod with controlled displacement equal to 2 mm/min.

The displacement is measured at CEA by an inductive LVDT sensor placed under the end plug side (lower part of device). The force is measured by a force transducer directly linked to the loading rod placed in the upper part of the device.

At PoliTO the displacement is controlled by a displacement sensor embedded in the tensile test machine and the force is measured by a force transducer directly linked to the loading rod placed in the lower part of the device.

3. Results and discussion

The dimensional stability and thermal behavior of the crystallized SAY has been studied in this work by Hot Stage Microscopy (HSM) from room temperature to 1400 °C (Fig. 1) , where the sample's height percentage (Relative Height) shows that the curve is almost flat up to 1200 °C and a decreasing trend starts at about 1300 °C. By increasing the temperature, the melting temperature onset is evident at about 1360 °C, and the measure was stopped at about 1390 °C. These results are in agreement with differential thermal analysis and dilatometry results done on SAY and reported in [4,11–13].

In order to measure the SAY refractoriness under load, the British Standard BS EN ISO 1893:2008 was used on two cylindrical pellets of SAY glass-ceramic loaded at 10 and 26 kPa at 1250 °C, 1 hour: in both cases the measured pellets' final height (8.40 mm) and diameter (8.87 mm) are unchanged respect to the initial ones, thus confirming a certain refractoriness of SAY glass-ceramic under these conditions.

Given the overall interesting behavior of the SAY glass-ceramic, corroborated by the thermal stability results described above, a slurry made of SAY powders and isopropanol was used to join SiC slabs, SiC/SiC tubes together and SiC/SiC tubes to SiC/SiC end-plugs, by the joining thermal treatment described above (1375 °C followed by a crystallization at 1235 °C, one hour) in a furnace under Ar flow.

Fig. 2 shows some examples of the obtained results: several SiC/SiC tubes were joined together (a) and closed by a SiC/SiC end-plug on one side (b) or both sides (c). The tube length ranges between 10 to 50 mm.

The CT-scan pictures in Fig. 3 (a–c) show the continuity of the joint all around the end-plug perimeter, the excellent wettability of SAY on SiC/SiC and SAY penetration inside the SiC/SiC end-plug porosity on a

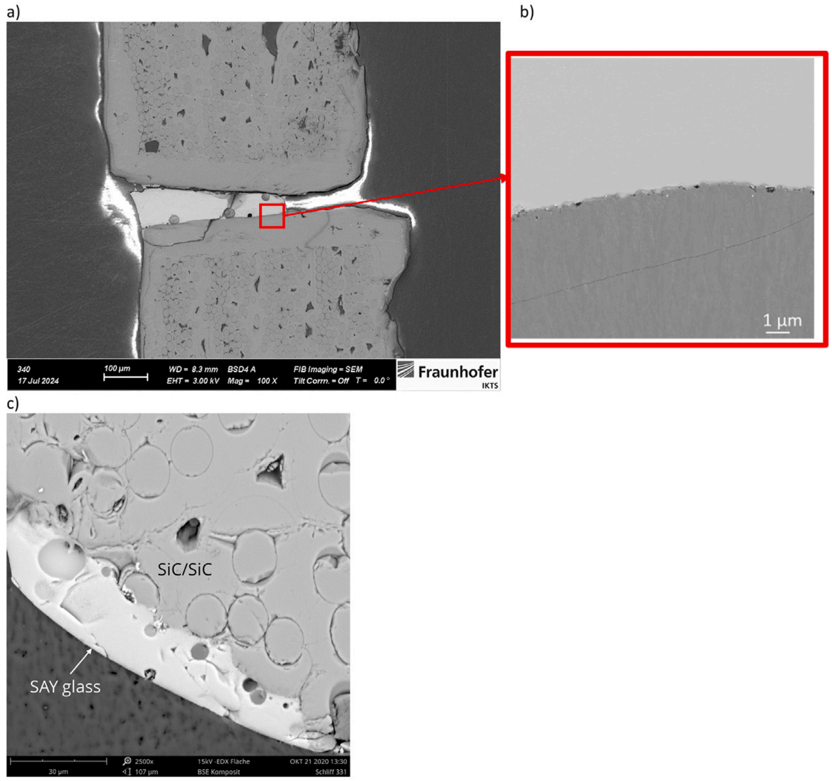

Fig. 5. SAY joined SiC/SiC tube by laser at TUD (Dresden, Germany): SEM cross section of the joined tubes (a), particular of the interface tube/SAY (b) and higher magnification (c) showing the excellent wettability of laser molten SAY on SiC/SiC.

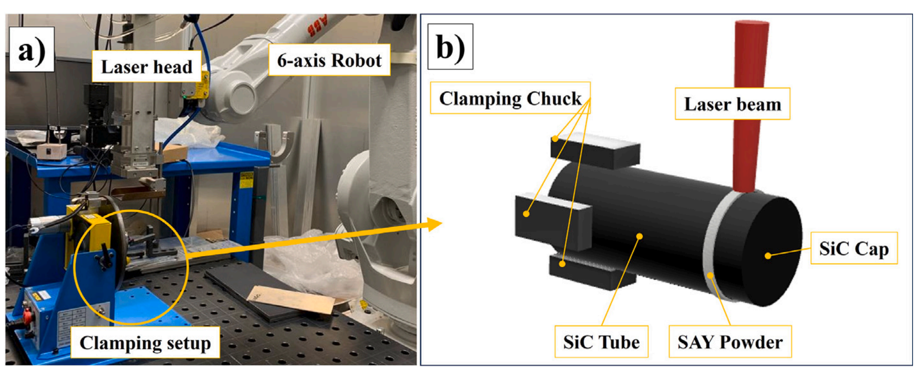

Fig. 6. Laser joining set up (a) and rotation device for tube/end-plug joints (b) at J-Tech@PoliTO.

typical sample. The joining process mechanism in the furnace consisted of a thermal treatment at 1375 °C, at which the SAY glass viscosity is low enough to penetrate not only inside the gap between tube and end-plug, but also to infiltrate part of the end-plug porosity (figure 3 c); the crystallization process of one hour at 1235 °C, allows the transformation of the glass into a glass-ceramic [16–18].

Fig. 3(d) shows the typical microstructure of these joints: the same crystalline phases already reported in the literature on SAY are visible: their composition has been confirmed by EDS, (not reported here), revealing the presence of the three crystalline phases (mullite, cristobalite and keivite) cited above.

Given the joining process feasibility by conventional furnace, the next step was aimed to find a localized heating source to join SiC/SiC tubes together and SiC/SiC tubes to SiC/SiC end-plug without heating the whole component, but in a pressure-less, localized manner.

Laser assisted joining [6,7] at TUD gave promising results as a pressure-less, localized heating joining technology suitable for SiC/SiC operating in a nuclear (and other) environment.

Activities done at TUD showed the possibility of obtaining SiC butt joints by laser localized heating and Y_2O_3-Al_2O_3-SiO_2 glasses of several compositions as joining materials. The laser assisted joining process mechanism has been thoroughly described in [7]. In summary, the laser beam is guided to obtain fast heating of the joining materials, which solidify in a glassy state. Due to the low viscosity, the glass penetrates the substrate up to 20 μm deep. With optimized laser parameters, the joined samples exhibit a 4-point bending strength of 132±32 MPa at room temperature for monolithic SiC joined samples [20].

These remarkable results suggested the possibility of sound joints also in case of SiC/SiC.

Within the project IL TROVATORE (https://www.iltrovatore-h2020.eu/) the glass-ceramic composition SAY was tested at TUD for the joining of SiC/SiC tubes by laser processing (Fig. 4–a).

The temperature distribution at the end of the heating process on the joined components' surface is shown in Fig. 4–b, c. Fig. 4–b shows that the laser heating covers just an approximate 17 mm of the SiC/SiC

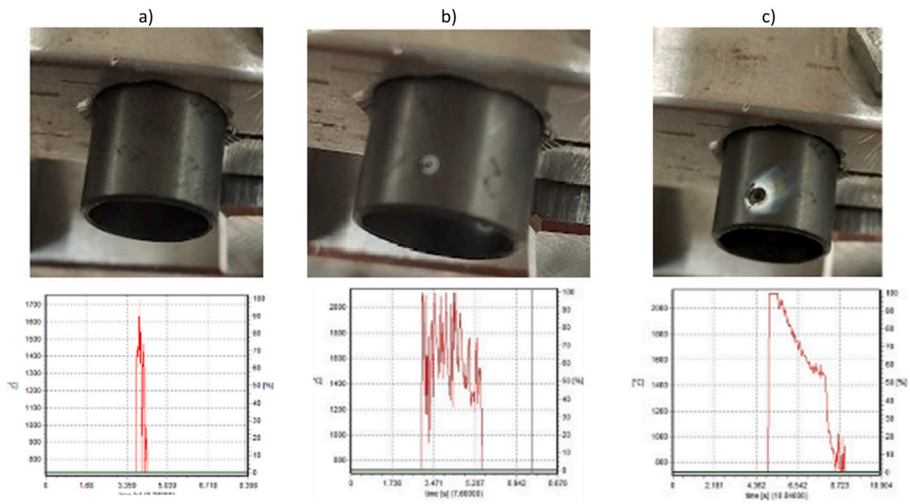

Fig. 7. Visual appearance of SiC/SiC tubes after laser heating at different laser power, in air, 3 seconds: 70 W (a), 75 W (b) 120 W (c).

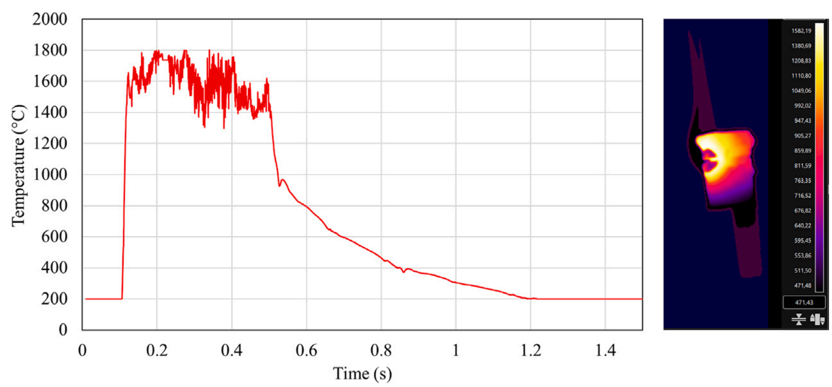

Fig. 8. SAY joined SiC/SiC tube by laser at POLITO (Turin, Italy): temperature measured during laser joining process.

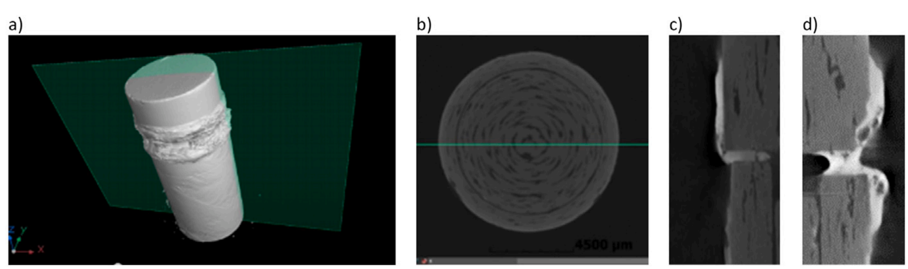

Fig. 9. CT-scan of a SiC/SiC tube closed by an end-plug: the joining material is the SAY glass-ceramic, the joining process was done by laser, in air, with an optimized set of parameters.

tubes, to minimize thermal stress on them. After 40 s the laser beam is switched off and further cooling is obtained by free convection.

It is to be noted that the SAY microstructure after this laser joining process is completely amorphous and differs to what was observed after joining by conventional heating in a furnace (Fig. 3).

Fig. 5 shows morphological results of the SAY joined SiC/SiC tube by laser at TUD: SEM cross-section of the joined tubes (a), particular of the interface tube/SAY (b) and higher magnification of it (c) show the excellent wettability of SAY on SiC/SiC. No crystalline phases can be observed in these micro-sections, which is consistent with the fast cooling typical of the laser process, compared to the slower one of the conventional heating in a furnace.

The behavior in a nuclear simulated environment of the two different SAY microstructures obtained after laser- or furnace-heated SAY is currently under investigation.

Following these promising results at TUD on SiC/SiC tubes, the laser at POLITO was used to join SiC/SiC tubes to SiC/SiC end-plugs: the set-up is shown in Fig. 6, with the rotating device designed for tube/end-plugs joints.

Effective laser–material interaction is critical: achieving the right balance between parameters is crucial and challenging, as widely analyzed in [21].

The laser power and its scanning speed, the repetition frequency and the scanning interval have a profound influence on SiC/SiC, as recently reported by [22].

Thus, considerable activity was aimed at finding the suitable laser parameters to join SiC/SiC to SiC/SiC end-plugs without detrimental effects on the composites. Details of the laser parameters optimization will be reported in a specific paper. Fig. 7 shows an example of this activity with the main representative steps of the optimization process,

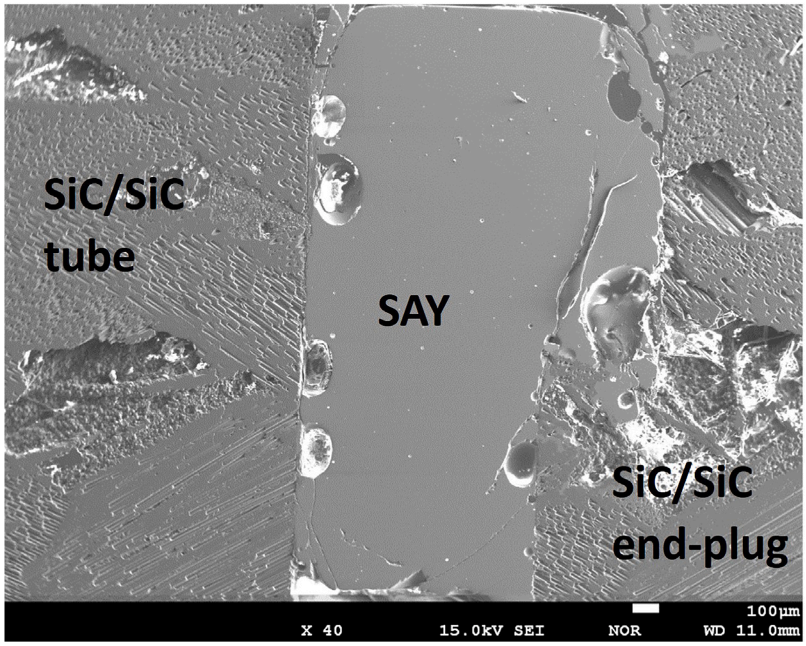

Fig. 10. FESEM of a SiC/SiC tube closed by an end-plug: the joining material is the SAY glass-ceramic, the joining process was done by laser, in air, with an optimized set of parameters. The polished cross section shows a uniform joined region with some porosity close to SiC/SiC.

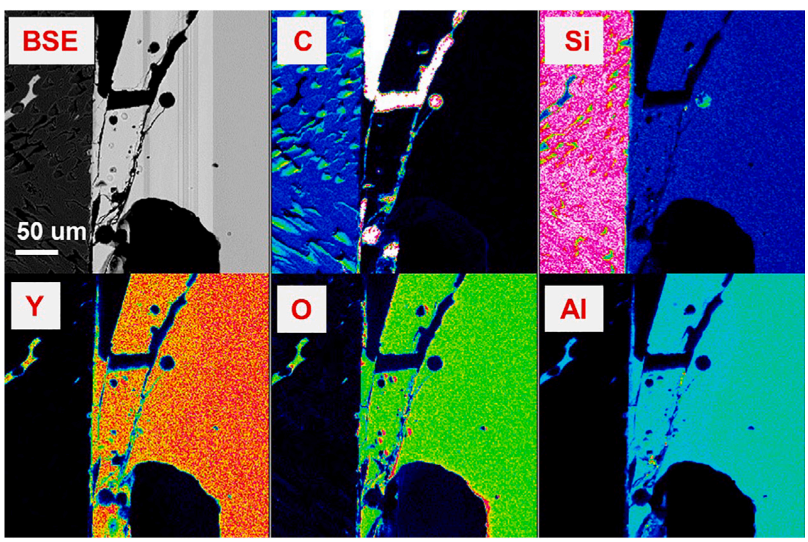

Fig. 11. Element map distribution of C, Y, Al, Si and O in the joint area, indicating the amorphous nature of the SAY and its infiltration in the SiC/SiC.

and the corresponding visual appearance of laser effects on the SiC/SiC tubes.

The laser parameter optimization to achieve a sound joint without detrimental effects on SiC/SiC was obtained by increasing the laser power by steps of 5 W starting from 60 W, while keeping the time constant at 3 s, in air. The maximum acceptable laser power (Fig. 7–b) for this SiC/SiC tube, in these operative conditions (air) was found at 75 W, 3 seconds: lower (Fig. 7–a) and higher power (Fig. 7–c) gave none or detrimental reactions on SiC/SiC, respectively.

The latter conditions (Fig. 7–c) caused the formation of a hole in the SiC/SiC tube, due to the formation of silica and its subsequent vaporization.

Further tests were conducted to optimize the joining of SiC/SiC tubes to the end-plug using SAY slurry: it can be observed in Fig. 8 that the laser does not cover a broad area of the SiC/SiC tubes, but is gradually concentrated along the circumference of the tube. The thermal cycle shown in Fig. 8 is recorded in the zone targeted by the laser, approximately corresponding to a length of 5 mm.

Initial, but encouraging results with SiC/SiC tubes joined to the end-plug by SAY slurry are shown in Fig. 9–a, b: a good wettability between SiC/SiC tubes and SiC/SiC end-plug can be observed in Fig. 9–c, d.

FESEM cross-section in Fig. 10 shows the joined region after polishing: a completely amorphous SAY is evident, with absence of visible reactions at the interface with SiC/SiC and with composition detected by EDS corresponding to the SAY one, as it can be observed in the element maps of Fig. 11. The amorphous structure of SAY after laser joining was expected, due to the intrinsically fast cooling of the laser process; if a crystalline structure is preferred, a heating treatment of the joined sample at the crystallization temperature (one hour at 1235 °C) would be necessary.

Despite the fast laser joining process, it can be seen in Fig. 10 that the glassy joining material is infiltrated in the SiC/SiC porosities; this

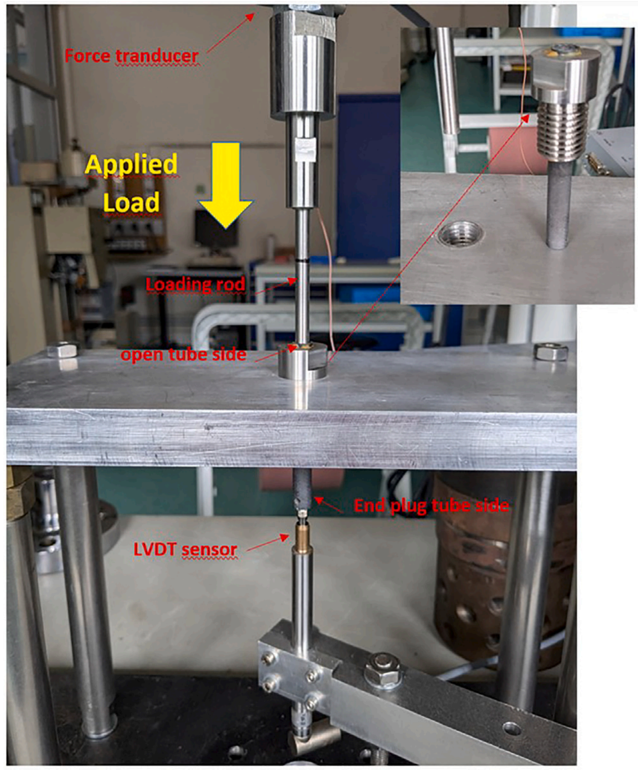

Fig. 12. Mechanical test set up at CEA to test SAY joined SiC/SiC tubes to end-plugs.

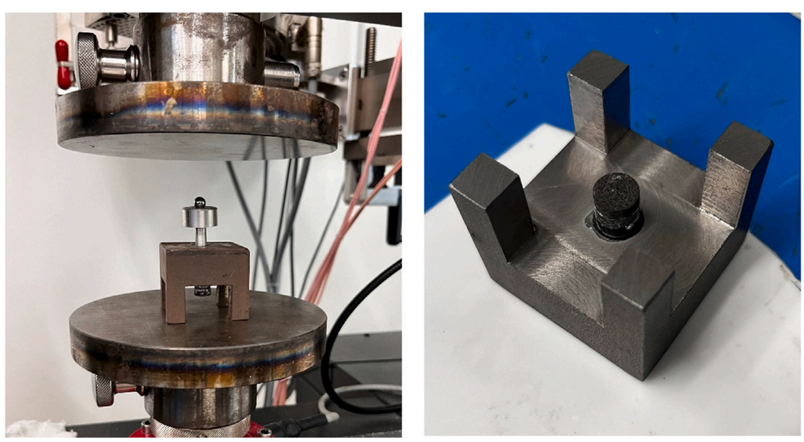

Fig. 13. Mechanical test set up at POLITO to test SAY joined SiC/SiC tubes to end-plugs.

feature can be beneficial in terms of bonding at the interface and also confirms what was observed for the laser joining process done at TUD on SiC/SiC tubes in Fig. 5.

The SAY-SiC/SiC interfaces still show some cracks and porosity, also visible within the joint area, but the interface is overall continuous. The CTE mismatch between SAY and SiC/SiC after laser joining does not seem to affect the integrity of the joint, and it will be verified by mechanical tests.

Mechanical tests on SAY joined SiC/SiC tubes to end-plugs have been done at CEA and at POLITO, on furnace joined and laser joined samples, for comparison purposes; both tests are done by measuring the force necessary to push out the end-plug from the tube, in compression, as illustrated in Figs. 12, 13.

The curves in Fig. 14 summarize the mechanical behavior responses from tests performed by CEA on SAY joined SiC/SiC tubes to end-plugs done at POLITO, with furnace- or laser-joining process : a compression force of about 1180 N has been measured on the best sample out of three furnace joined SiC/SiC tubes to end-plugs, while laser joined ones gave lower values, with a maximum of about 600 N on one of them. It is worth noting the completely brittle behavior of all three furnace joined samples. A very different shape for the mechanical test curve was measured for all four laser joined samples.

Fig. 15 provides a possible explanation for this behavior: it shows the compressive load and acoustic emission (EA) results on the laser joined sample T22P, (T22P, see caption in 15): for this sample, the SiC/SiC end-plug is detached from the tube at 621 N, but some of the SAY joining material between the inner surface of the tube and the outer surface of the end-plug is still keeping it bonded (see inset), resulting in a weak friction force between tube and end-plug.

What it is clear from the typical morphology of the end-plugs after mechanical tests (as in Fig. 15 and inset) is that the SAY did not flow enough between tube and end-plug during this laser joining process:

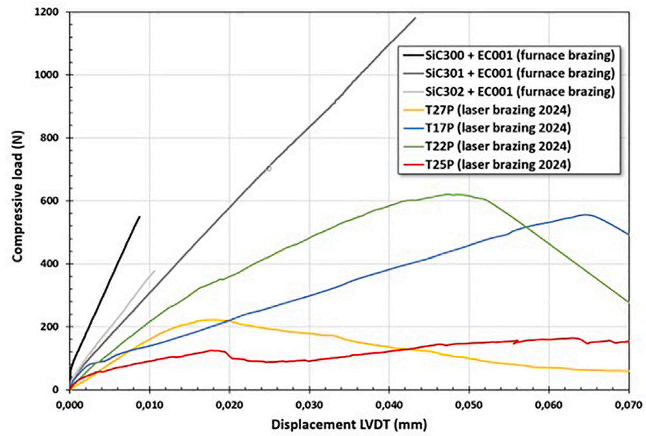

Fig. 14. Comparison of mechanical tests performed at CEA between SiC/SiC composite tubes joined to end-plugs by SAY between laser joined and furnace joined.

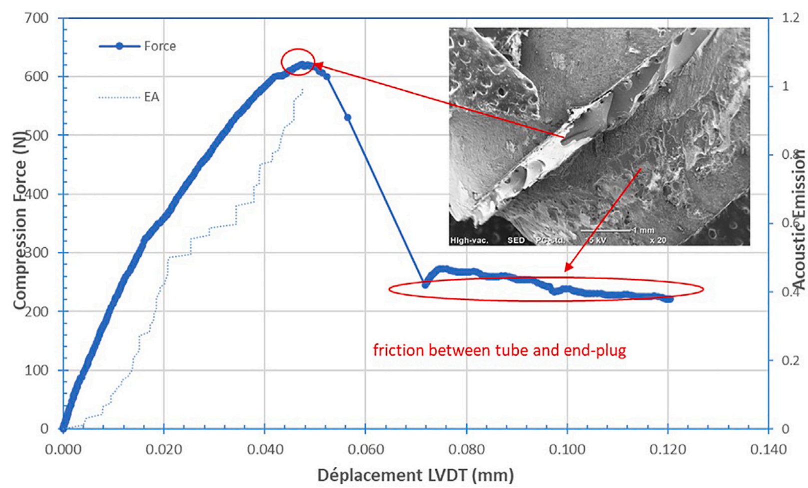

Fig. 15. Mechanical test result on laser joined SiC/SiC tube to SiC/SiC end-plugs by SAY (T22P, Fig. 14) : detail of the compressive load and acoustic emission (EA): at 621 N the SiC/SiC endplug is detached from the tube, but some of the SAY joining material between the inner surface of the tube and the outer surface of the end-plug is still keeping it bonded by a weak friction force (see inset).

the joining material was mainly found on the tube cross-section (the annular section) and just a very limited amount of SAY is present between the inner surface of the tube and the outer surface of the end-plug.

Values of about 2100 N have been achieved and measured at POLITO, Fig. 16: the inset shows the presence of SAY on the end-plug external surface. A partial detachment of the SiC/SiC tube internal surface was observed in some places, due to the strong bond obtained with the end-plug.

4. Conclusions

Pressure-less, localized heating, laser-assisted joining of SiC/SiC tubes to SiC/SiC end-plugs by two different diode laser-based processes, both operating in the infrared, has been demonstrated using a silica-alumina-yttria-based glass as joining material.

In one case (TUD), the laser joining process aimed to heat the SiC/SiC tubes to the temperatures needed for the joining while in the second case (POLITO), the laser directly targeted the glass in the localized joining area. In both cases the laser was focused on the region to be joined and both SiC and glass were heated, even though they absorb differently.

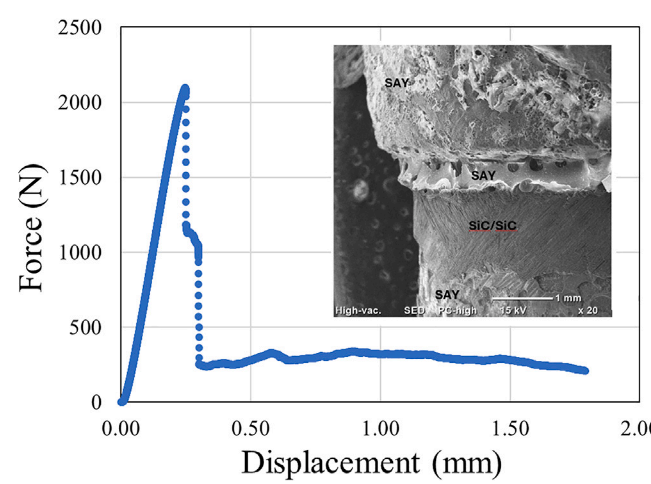

Fig. 16. Mechanical test result on one laser joined SiC/SiC tubes to SiC/SiC end-plugs by SAY (POLITO). Inset: particular of the end-plug after mechanical test, showing the presence of amorphous SAY and partially detached SiC/SiC tube internal surface.

The joining material is completely crystallized after joining in a conventional furnace, while it is completely amorphous in the case of laser joining.

The joints mechanical strength, measured by using a push test aimed to detach the end-plug from the tube reached a maximum of 1200 N and 2100 N (best values) for furnace and laser joined samples, respectively.

Further research is needed to improve the quality of laser joined SiC/SiC, but the obtained preliminary results are very encouraging, and to the best of authors' knowledge, never obtained before.

This work may pave the way for a wider use of joined CMC, specifically but not restricted to the nuclear industry, where heating several meter-long components to join just a few mm long portion is considered unpractical.

CRediT authorship contribution statement

Monica Ferraris: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Manuela De Maddis:** Methodology, Investigation, Conceptualization. **Dario Basile:** Methodology, Investigation, Data curation. **Khurshid Aliev:** Investigation. **Dario Alidoost:** Investigation. **Alessandro Benelli:** Visualization, Investigation, Formal analysis. **Stefano De La Pierre:** Methodology, Investigation, Data curation. **Valentina Casalegno:** Methodology, Investigation, Data curation. **Marion Herrmann:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shuigen Huang:** Investigation. **Jef Vleugels:** Investigation. **Christophe Lorrette:** Investigation. **Cédric Sauder:** Investigation. **Konstantina Lambrinou:** Investigation.

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Declarations

Part of the subject matter of this manuscript is covered under the patent application no. 102025000010533 filed by the Politecnico di Torino.

Declaration of competing interest

Part of the research leading to these results has received funding from the Euratom Research and Training Programme 2021–2025 under Grant Agreement No. 101059511''- Project SCORPION (SiC Composite Claddings: LWR Performance Optimisation for Nominal and Accident Conditions) and Il Trovatore. The IL TROVATORE project receives funding from the Euratom research and training programme 2014–2018 under grant agreement N° 740415.

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