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Review article

Joining of oxide-oxide ceramic matrix composites – A review

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ABSTRACT

Oxide–oxide ceramic matrix composites are attractive for high-temperature structural applications, but their industrial use in complex assemblies requires reliable joining technologies. This review critically compares glass-ceramic bonding, brazing, adhesive or polymer-derived routes, and mechanical fastening for ox–ox CMCs, focusing on processing conditions, thermo-mechanical compatibility, joint strength, ageing resistance, thermal cycling, and flame exposure. Reported apparent shear strengths range from 2 to 5 MPa for conventional active brazes, 7–18 MPa for glass-ceramic joints, and up to 49 MPa for Ti-based brazed butt joints, showing the strong influence of joint geometry and filler infiltration. SiO_2–Al_2O_3–CaO–MgO and SiO_2–Al_2O_3–TiO_2–Y_2O_3 glass-ceramics showed stable interfaces after ageing at 850–930 °C and survived direct flame exposure at 900 °C. Overall, glass-ceramic joining currently offers the best balance between oxidation resistance, thermo-mechanical compatibility, and durability, whereas brazing provides higher strength but greater sensitivity to CTE mismatch and residual stresses.

1. Introduction

This Introduction is structured as follows: first, the general strategic relevance of ceramic matrix composites (CMCs) is outlined; second, oxide-oxide ceramic matrix composites (ox–ox CMCs) are introduced in comparison with non-oxide systems to clarify their specific advantages and limitations; finally, the focus is narrowed to ox–ox CMCs as the target material system of this review.

Ceramic matrix composites are high-performance materials widely recognized for their exceptional thermo-mechanical properties and their suitability for operation in extreme environments [1]. Compared with conventional metals, CMCs offer significantly higher maximum service temperatures, higher specific strength, and superior resistance to creep, fatigue, oxidation, and corrosion. These characteristics enable CMCs to maintain mechanical integrity and dimensional stability under conditions where metallic alloys typically suffer from softening, accelerated oxidation, or creep deformation. As a result, CMCs are increasingly regarded as irreplaceable materials for advanced engineering applications that demand performance beyond the limits of conventional metallic systems [2,3].

Quantitatively, CMCs can operate at temperatures exceeding 1200 °C, compared with approximately 600–1100 °C for most superalloys, while simultaneously offering higher specific strength (over 200 MPa·cm^3/g compared to 50–150 MPa·cm^3/g), and superior resistance to creep and fatigue at elevated temperatures [4]. These advantages translate into weight reduction, increased operating temperatures, and reduced cooling requirements in high-performance components. In addition, CMCs exhibit superior thermal shock resistance and reduced cooling requirements, enabling higher engine operating temperatures and improved energy efficiency in turbine systems.

In this context, CMCs currently represent the leading class of materials for extreme-service components. Reinforcement of the ceramic matrix with ceramic fibers improves fracture toughness, damage tolerance, and resistance to thermal shock, while retaining high specific strength and chemical stability. These combined mechanical, thermal and chemical properties make CMCs particularly suitable for demanding applications in the energy, aerospace and industrial processing sectors [5]. CMCs can also be employed as substitute materials for metals that cannot withstand severe thermal conditions, as increasingly required by the energy transition.

To define the material framework of this review, a distinction between oxide and non-oxide CMCs is provided. The following comparison between these two families is introduced to clarify the specific role and relevance of oxide-based systems, rather than to provide a comprehensive review of all CMC material classes. Based on the nature of constituent materials of both matrix and fibers, fiber-reinforced CMCs can be broadly classified into two main categories: non-oxide-based and oxide-based CMCs [6]. The former includes carbides, nitrides, and borides,

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with representative examples such as silicon carbide, silicon nitride, aluminum nitride or titanium diboride TiB_2 matrices reinforced with non-oxide-based reinforcements (i.e. carbon or silicon carbide fibers) [4]. The latter comprises oxide matrices, such as aluminum oxide, aluminosilicate, silicon oxide or zirconium oxide, reinforced with aluminum oxide fibers [7,8]. In both systems, fibers can effectively hinder crack propagation within the material, thereby improving mechanical strength, hardness, toughness and reliability [7].

Non-oxide-based CMCs are suitable for higher temperature applications, with service temperatures approaching 1500 °C [9], Ultra-High Temperature Ceramic Matrix Composites (UHTCMCs) can withstand 2000 °C for short-term applications, such as reentry conditions [10]; however, their use is limited by their oxidation sensitivity and higher costs. Ox–ox CMCs were developed to overcome these limitations and to expand their range of applications, offering superior environmental stability and longer service life in oxidizing atmospheres, where non-oxide systems may undergo rapid degradation [11]. Although ox–ox CMCs are generally limited to operating temperatures below 1200 °C [12], they exhibit intrinsic oxidation resistance, which makes them particularly suitable for applications in harsh environments, such as the hot sections of turbine engines without the need for complex or highly protective coating systems [13,14]. Using oxides for all constituents of the composites, i.e. fibers, matrices, and interface coatings, offers superior environmental stability, though it may result in detrimental effects on mechanical performance such as reduced creep resistance [15–17]. For this reason, research interest in ox–ox CMCs is increasing, aiming to overcome the limitations of their application temperatures [18]. Ox–ox CMCs are increasingly being adopted in place of metallic alloys for high-temperature components such as combustor liners, exhaust nozzles, and flame tubes, where they enable both higher thermal efficiency and significant weight reduction in engines and vehicles [13,19,20]. This intrinsic environmental stability makes them particularly attractive for exhaust systems and other hot-gas path components, where conventional metallic alloys often suffer from accelerated degradation, scale formation, or coating failure over time. Additional benefits of ox–ox CMCs include the lower cost of raw materials and component manufacturing [19] compared with SiC-based composites, since they involve lower processing temperatures in the manufacturing route. However, the low thermal conductivity of ox–ox CMCs results in higher thermal strains compared with non-oxide composites. In addition, the high level of open porosity of ox-ox CMCs, around 30%, limits the matrix-dominated mechanical strength and restricts their application in components requiring higher strength [21]. Recent advances in surface finishing technologies for ox–ox CMCs have further enhanced their functional performance. Improved control of surface roughness not only benefits aerodynamic and thermal behavior but also contributes to superior damage tolerance by mitigating the initiation of microcracks and by increasing resistance to thermal cycling. Taken together, these attributes consolidate ox–ox CMCs as a compelling alternative to metals in demanding high-temperature applications [22].

Summarizing, in the last years the industrial interest in ox–ox CMCs has significantly increased, particularly in the aerospace and energy sectors, where the demand for lightweight materials capable of operating above the temperature limits of metallic alloys continues to grow. Ox–ox CMCs are currently being developed for combustor liners, exhaust structures, thermal protection systems, hot-gas ducts, and industrial furnace components, with ongoing efforts focused on improving creep resistance, matrix densification, fiber/matrix interface stability, and damage tolerance at temperatures approaching 1200 °C. At the same time, the transition from laboratory-scale components to large and complex industrial assemblies has highlighted the critical importance of reliable joining technologies. Since many high-temperature structures cannot be manufactured as monolithic components due to geometrical, processing, transportation, and maintenance constraints, robust joining solutions are essential to enable modular design, repairability, integration with metallic substructures, and scalability toward industrial implementation. This challenge becomes particularly relevant as current industrial developments increasingly target larger combustor liners, hot-gas ducts, radiant tubes, thermal protection systems, and modular turbine components, whose dimensions and complexity often exceed the practical limits of monolithic manufacturing. Despite this technological need, the literature on joining of ox–ox CMCs remains limited and fragmented compared with the extensive research available for non-oxide CMC systems.

1.1. Scope and literature selection criteria

This review adopts a focused and application-driven approach to the analysis of joining technologies for ox–ox CMCs. The literature survey was conducted by screening peer-reviewed journal articles and conference proceedings available in major scientific databases, with particular emphasis on studies addressing the joining of ox–ox CMCs for high-temperature structural applications.

The selection criteria prioritized studies reporting experimental joining approaches and providing quantitative performance data, such as joint mechanical strength (shear and/or flexural), thermal stability, ageing or creep behavior, and environmental durability under oxidizing or combustion-like conditions. Studies were included when they directly addressed ox–ox CMC systems or when their findings were clearly transferable to all-oxide composite architectures.

Studies focusing exclusively on non-oxide CMC systems, not involving joining processes, or lacking sufficient performance-related information were excluded. Given the still relatively scarce and heterogeneous available literature on ox–ox CMC joining, this review does not follow a formal systematic-review protocol. Instead, it aims to provide a critical and comparative synthesis of the most relevant and representative studies, highlighting key trends, limitations, and open challenges in the field.

2. Processing, thermo-mechanical behavior and application-driven requirements of ox–ox CMCs

The performance of CMCs is strongly influenced by the nature of the matrix, the reinforcement, and the fabrication method. Selecting appropriate materials and fabrication techniques is crucial for optimizing properties such as strength, toughness, and thermal stability. Factors including production cost, technology availability, and system compatibility also influence their adoption. In recent years, increasing attention has been devoted to manufacturing processes capable of reducing processing time and cost while maintaining or enhancing mechanical and thermal performance [4,23]. Ox–ox CMCs have been developed and continuously refined over the decades and are currently commercialized by companies such as COI-ATK (USA), WPX Faserkeramik GmbH and Walter E. C. Pritzkow Spezialkeramik (WPS) (Germany). One of the most widely adopted methods involves the infiltration of a ceramic fabric with a ceramic matrix slurry, followed by lamination. Subsequently, the infiltrated fabrics can be placed into a press mold and compacted by applying pressure, leading to a higher fiber volume fraction and improved composite quality. Furthermore, textile-based ox–ox CMCs can be produced by vacuum-assisted lamination, which enables the fabrication of complex-shaped components with high mechanical resistance [24]. Other manufacturing routes involve prepreg-based lay-up techniques [25] and winding-based processes [26]. In these processes, fiber preforms are assembled by either stacking impregnated layers or winding fiber tows into tailored architectures. This is followed by consolidation through pressing and high-temperature sintering.

A comprehensive overview of the mechanical and thermal properties of ox–ox CMCs is provided in Ref. [27]. Their exceptional fracture toughness and crack resistance arise from a characteristic crack-bridging mechanism. When subjected to stress, the ceramic matrix cracks at an elongation of approximately 0.05%, similar to conventional ceramics;

however, in CMCs, embedded fibers act as bridges across these cracks, effectively transferring load across the crack. For this mechanism to work effectively, a relatively weak bond at the fiber/matrix interface is required, allowing the matrix to slide along the fibers. This promotes energy absorption and crack deflection, rather than forcing the fibers to carry the entire load. In non-oxide CMCs, a weak fiber/matrix interface is typically achieved by applying a thin coating of pyrolytic carbon or boron nitride on the fibers, facilitating fiber pull-out at crack surfaces. In ox–ox CMCs, the naturally high porosity of the matrix inherently provides the required weak bonding at the fiber/matrix interface [28].

Fiber orientation further contributes to the anisotropy in the mechanical, thermal and electrical properties of ox–ox CMCs. These materials generally exhibit excellent electrical insulating capabilities, and due to their high porosity, offer superior thermal insulation compared with monolithic oxide ceramics.

Ox–ox CMCs also exhibit low dielectric constants, which makes them suitable candidates for higher service life applications like hot-gas filters and exhaust components [29,30].

Previous works have thoroughly investigated the manufacturing processes and mechanical and thermal properties of ox–ox CMCs [4,31,32]. Ox–ox CMCs are typically characterized by low density (approximately 2–3 g/cm^3), fiber volume contents between 35% and 45%, and open porosity levels of 25–35%. Common oxide reinforcements include corundum, corundum-mullite fibers, which provide good chemical and thermal shock resistance, as well as low thermal conductivity and coefficient of thermal expansion (CTE), around 3.7–5.3 $\times$ 10^{-6} K^{-1} for mullite-based insulators [33,34], 3.2–4.2 $\times$ 10^{-6} K^{-1} for cordierite-mullite-alumina-based ceramics [35] and 6.5 $\times$ 10^{-6} K^{-1} (40–100 °C) for alumina-based systems [36]. Ox–ox CMCs exhibit relatively low CTE values, generally ranging between 2 for aluminosilicate matrix with alumina/mullite fiber [5] and 8.6 $\times$ 10^{-6} K^{-1} for alumina-zirconia matrix reinforced with alumina fiber [37]. While low CTE is beneficial for dimensional stability at high temperature, the relatively low thermal conductivity of these composites can lead to significant thermal gradients and associated stress. Moreover, the CTE of ox–ox CMCs depends on fiber architecture and orientation, which must be accounted for during joint design to limit anisotropic effects and thermal stress concentrations [38].

Ox–ox CMCs have been extensively characterized for high-temperature applications [15], including tensile, flexural, creep and interlaminar shear testing [22]. Several studies have demonstrated their ability to retain mechanical integrity under prolonged thermal exposure and aggressive service environments. In particular, ox–ox CMCs have shown good corrosion resistance at high temperatures in calcium-magnesium aluminosilicate environments representative of turbine operation [39], as well as creep resistance in combustion atmospheres, with reported lifetimes of up to 25 h under applied stresses below 72% of ultimate tensile strength [40]. Additional investigations have addressed their behavior under thermal ageing [41], resistance to aluminum oxychloride infiltration [42], and tensile creep behavior in air and steam at high temperatures [43]. Ox–ox CMCs are currently attracting increasing industrial interest for components operating under severe thermo-mechanical and oxidizing environments, particularly in aerospace, energy conversion, and high-temperature industrial processing systems. In aerospace propulsion, ox–ox CMCs have been investigated for combustor liners, exhaust nozzles, thermal shields, and hot-gas duct components, where their oxidation resistance and low density enable reduced cooling requirements and improved fuel efficiency compared with metallic superalloys [19,22]. In gas turbine systems, these composites are considered promising candidates for flame tubes and combustor structures operating at temperatures approaching 1100–1200 °C [5,19]. Ox–ox CMCs are also being explored for thermal protection systems in reusable space vehicles and hypersonic platforms due to their thermal shock resistance and stability in oxidizing atmospheres [8,14].

Beyond aerospace applications, ox–ox CMCs are increasingly employed in industrial furnaces, radiant tubes, hot-gas filters, and heat-treatment systems, where resistance to thermal cycling and corrosive combustion environments is essential [21]. Their relatively low thermal conductivity and excellent environmental stability make them attractive for long-term operation in combustion atmospheres, particularly where metallic systems suffer from oxidation, creep, or coating degradation. Recent developments are further focused on improving matrix densification, creep resistance, fiber/matrix interface stability, and damage tolerance to extend the operational lifetime of ox–ox CMC components under cyclic high-temperature loading [27,41,44,45]. Representative high-temperature applications currently targeted for ox–ox CMCs are schematically summarized in Fig. 1. However, the implementation of ox–ox CMCs in large-scale and complex engineering systems strongly depends on the availability of reliable joining technologies capable of maintaining structural integrity and thermo-mechanical compatibility under service conditions.

3. Joining of ox-ox CMCs

When manufacturing large or complex components for a specific application, and when considering all the required operating conditions that the material must withstand, the joining of the individual parts becomes a critical step that must be carefully designed [46]. Effective joining methods must be selected to obtain reliable, integrated and mechanically resistant structures that ensure the successful performance of the whole system. The performance of the joints can be evaluated through several criteria, including the thermal expansion compatibility between the joined substrates and the joining material, mechanical strength, and resistance to degradation under thermal and environmental loading. Joint quality is evaluated by mechanical testing, such as flexural and creep tests, as well as single lap (SL) and single lap offset (SLO) shear tests which are commonly used to measure the apparent shear strength of the joints. These tests can be performed at room or at high temperature to evaluate the joint behavior under representative service conditions. The mechanical testing data reported in the literature provide valuable insight into joint performance, damage mechanisms, and failure modes in ox–ox CMC assemblies [47–50], nanoindentation measures the local elastic modulus and examines microstructure–property relationships [51,52], whereas non-destructive techniques such as acoustic ultrasonic and computed tomography are used to detect inhomogeneities and to correlate internal features with mechanical strength [53].

Thermal ageing tests are essential for evaluating the long-term stability and durability of ox–ox CMCs and their joints under high-temperature service conditions. In the literature, ox–ox CMCs are commonly subjected to isothermal ageing at temperatures around 1200 °C, which is close to the maximum recommended operating temperature for materials like Nextel™ 610 fibers. Ageing durations typically range from 100 to 500 h, with some studies extending up to 1000 h [44,45,48]. Samples are usually heated at controlled rates (e.g., 10 °C/min) to the target temperature, held for the desired duration, and then cooled gradually to avoid thermal shock.

In addition to isothermal ageing, cyclic thermal shock tests are frequently employed to simulate realistic service conditions, in which specimens are repeatedly heated to high temperatures (e.g., 1100 °C) and rapidly cooled and quenched in water [48]. Such tests are particularly relevant for joined components, as thermal gradients and residual stress at joint interfaces may accelerate damage initiation, microcracking, or delamination. The combined use of isothermal ageing and thermal cycling therefore provides a comprehensive assessment of joint reliability and long-term performance [54].

3.1. Joining challenges for ox-ox CMCs

The main requirements for joints in ceramic matrix composites are to maintain structural integrity under high-temperature service conditions

Fig. 1. Representative applications of ox–ox CMCs in high-temperature aerospace, energy, and industrial systems, highlighting the critical role of reliable joining technologies for structural integrity, thermal durability, and integration of complex assemblies.

and to exhibit mechanical strength and thermal stability comparable to, or compatible with, the base ceramic materials [9,55]. In the case of

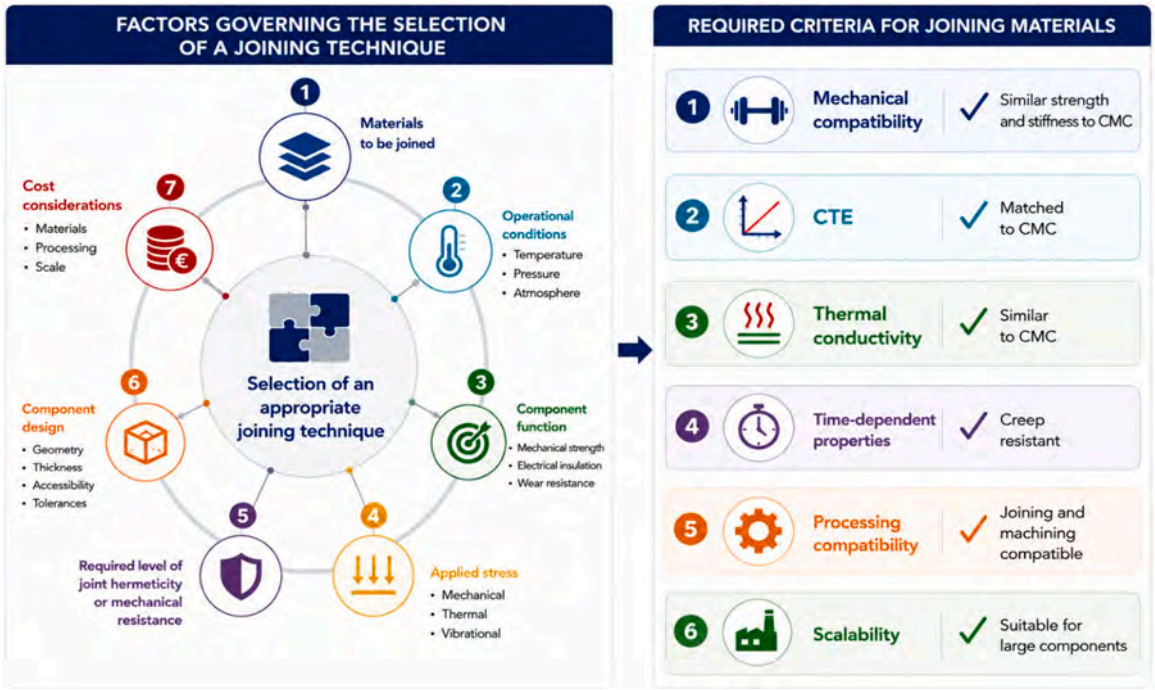

Fig. 2. Principal factors governing the selection of joining technologies for oxide–oxide ceramic matrix composites (ox–ox CMCs) and the corresponding requirements for joining materials. Reliable joints require thermo-mechanical compatibility with the composite, processing compatibility, and suitability for long-term service and large-scale applications.

ox–ox CMCs, joints must withstand service temperatures typically in the range of 900–1200 °C, depending on the manufacturing route, and should achieve shear strength values comparable to the interlaminar shear strength of the composites (typically in the range of 8–22 MPa) [56,57].

As a general rule, the selection of an appropriate joining technique for a given component depends on several factors, including: (1) the materials to be joined; (2) operational conditions, such as temperature, pressure and atmosphere; (3) component function (mechanical strength, electrical insulation, wear resistance, etc.); (4) applied stress; (5) the required level of joint hermeticity or mechanical resistance; (6) component design and (7) cost considerations. Accordingly, joining materials should meet several criteria, including mechanical properties similar to those of the CMC, a coefficient of thermal expansion closely matched to that of the CMC, a thermal conductivity similar to that of the CMCs, acceptable time-dependent properties, compatibility with processing and machining techniques, and feasibility for application in large-scale components.

The principal parameters governing the selection of joining technologies for ox–ox CMCs are schematically summarized in Fig. 2.

3.1.1. Similar joining of ox-ox CMCs

Similar joining refers to the joining of substrates having the same or very similar composition, such as ox–ox CMC-to-ox–ox CMC assemblies. In these configurations, the use of oxide-based joining materials generally minimizes thermal expansion mismatch and reduces the residual stresses generated during cooling from the joining temperature and subsequent thermal cycling. Consequently, similar joining is usually less critical from a thermo-mechanical standpoint than dissimilar joining involving metals or non-oxide ceramics.

However, achieving reliable joints still requires careful control of microstructural compatibility between the joining material and the composite architecture, preservation of the fiber/matrix damage-tolerant mechanisms, and limitation of residual porosity at the joint interface. For this reason, most joining approaches developed for similar ox–ox CMC assemblies are based on oxide-derived systems, particularly glass-ceramics, which offer good chemical compatibility and oxidation resistance. Despite the reduced thermal mismatch, long-term durability under thermal ageing, thermal cycling, and aggressive service environments remains a key challenge for high-temperature ox–ox CMC applications.

3.1.2. Dissimilar joining of ox-ox CMCs

In contrast, dissimilar joints involve different materials, such as two CMCs of different compositions, or a CMC and a ceramic or a metal.

Among the various challenges associated with dissimilar joints, one of the most critical is the thermal mismatch between the adherends, particularly in ox–ox CMC-to-metal configurations. The difference in CTE values can be significant. As previously discussed, ox–ox CMCs typically exhibit CTE values lower than 9×10^{-6} K^{-1} , whereas metals generally show higher values, ranging from 10 to 23×10^{-6} K^{-1} [58]. During heating and cooling cycles, this mismatch can generate substantial thermal stresses, which represent one of the main sources of damage and reliability issues in joined assemblies because they may promote crack initiation, interfacial debonding, and delamination. To mitigate these effects, suitable joining materials (hereafter also referred to as “interlayers”) together with tailored joint geometries are commonly employed.

Thermal expansion mismatch does not only constrain the selection of the joining material, but also strongly influences the residual stress state that develops during cooling from the joining temperature and during subsequent thermal cycling. In constrained bi-material joints, the mismatch stress scales with the product $\Delta CTE \cdot \Delta T$ and with the effective constraint stiffness (e.g., proportional to $E/(1-\nu)$). As a consequence, even moderate differences in thermal expansion can generate tensile stresses sufficient to promote microcracking, interfacial debonding, or delamination in the CMC/interlayer region. Accordingly, mitigation strategies typically combine: (i) compliant or CTE-graded interlayers, (including porous or composite interlayers, glass-ceramics or particle-filled braze layers) to smooth the CTE mismatch and reduce effective stiffness; (ii) joint geometries that minimize peel and bending stresses, such as butt, scarf, or stepped-lap configurations, fillets, and overlap optimization; and (iii) processing routes that limit thermal gradients and allow stress relaxation, for example through controlled heating and cooling rates or stress-relief dwells or anneals. Finite-element studies on ceramic–metal joints consistently show that joining material elastic modulus/CTE ranking and thickness are first-order design parameters controlling peak tensile stresses and can be used to screen candidate interlayers prior to experimental trials [59,60]. An optimized interlayer thickness can significantly enhance joint reliability by balancing mechanical compliance with adequate load transfer between the joined substrates. In addition, a recent study suggests that the implementation of an overlaying lap joint with the longest possible overlapping length is preferred from a structural design standpoint, to ensure maximum strength [61]. Another important aspect to consider is the different nature of the joining materials compared to the ox–ox composites. While ox–ox CMCs are inherently resistant to oxidation, some materials, especially brazing alloys, may exhibit limited oxidation or corrosion resistance under service conditions. Additionally, interfaces between the ox–ox CMC and the joining material may represent preferential paths for environmental attack, leading to accelerated degradation, interfacial weakening, or loss of mechanical integrity. Consequently, the selection and development of oxidation-resistant filler materials and/or protective coatings for the joints are crucial to ensure long-term durability of joined ox–ox CMC components.

The following sections therefore examine representative solutions for both similar and dissimilar joints in ox–ox CMCs, highlighting how glass-ceramic, brazed, adhesive, and mechanical joining approaches address, with different levels of success, the design challenges outlined above.

Fig. 3 schematically compares the main characteristics and challenges associated with similar and dissimilar joining approaches for ox–ox CMCs, highlighting the role of thermal expansion mismatch, interfacial compatibility, and stress mitigation strategies.

3.2. Joining materials and methods for ox-ox CMCs

To enable a meaningful comparison among the different joining routes, the approaches reviewed in this section are evaluated based on application-driven performance criteria. These include: (i) maximum demonstrated service temperature or thermal exposure, including ageing and thermal cycling; (ii) joint mechanical performance, expressed in terms of shear and/or flexural strength, with explicit reference to the test configuration; (iii) time-dependent behavior and thermal stability, such as creep, damage accumulation, interface integrity after exposure; and (iv) environmental durability, particularly oxidation resistance and, where available, flame or combustion-like exposure. These metrics are compared against the typical requirements for ox–ox CMC joints, which must sustain the maximum in-service temperature of the composite (≈ 900–1200 °C) and should reach joint shear strength comparable to the interlaminar shear strength of the composite (≈ 8–22 MPa).

Efficient joining materials and techniques are essential to integrate CMCs into high-performance structures. Despite extensive research on joining technologies for ceramic materials in general, the literature specifically addressing ox–ox CMC joining remains relatively limited. The most common methods used for joining CMCs include adhesive bonding, brazing, transient liquid phase bonding, microwave-assisted joining, laser-assisted joining, diffusion bonding, as well as the use of pre-ceramic polymers, MAX phases and glass-ceramics as joining materials [62]. However, for ox–ox CMCs, only a subset of these techniques has been systematically investigated and validated.

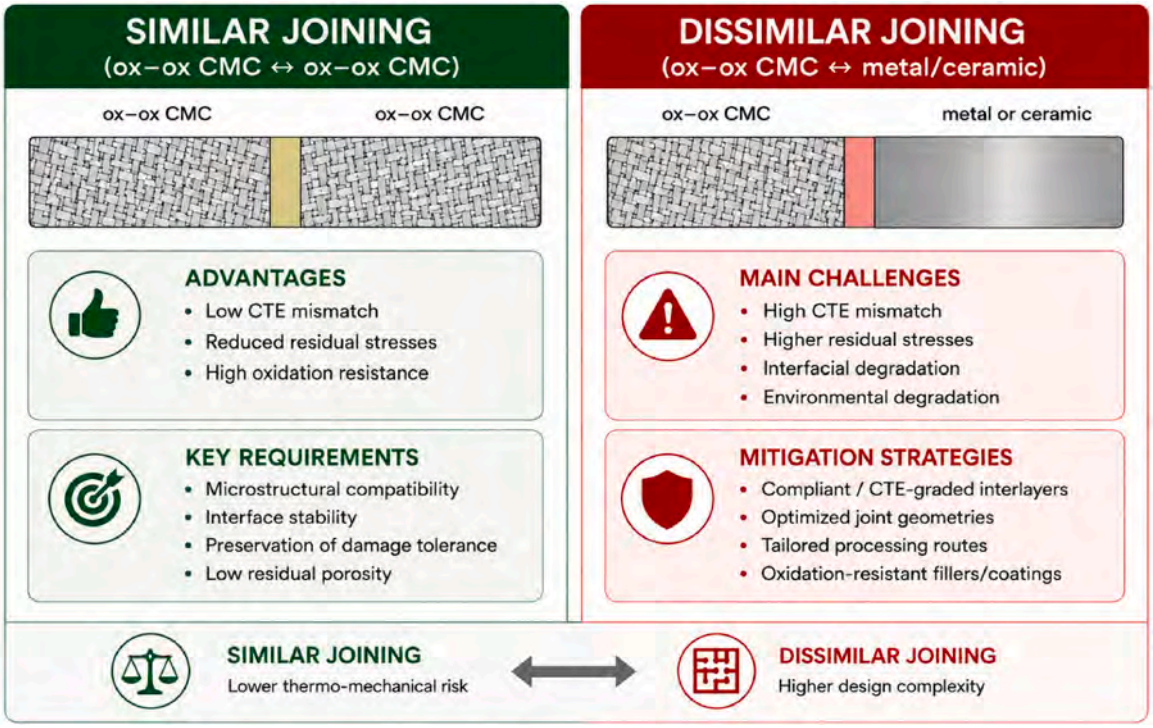

Fig. 3. Comparison between similar and dissimilar joining approaches for oxide–oxide ceramic matrix composites (ox–ox CMCs). Similar joining benefits from reduced thermal-expansion mismatch and lower residual stresses, whereas dissimilar joining introduces additional challenges related to thermo-mechanical incompatibility, interfacial degradation, and long-term durability.

To be effective, the joining material must withstand high temperatures without degradation during service, exhibit adequate wetting behavior on the substrates, and possess a coefficient of thermal expansion compatible with that of the composite to minimize thermal mismatch stresses. In addition, joined systems should retain mechanical strength, remain chemically stable under service conditions and be compatible with scalable processing routes.

Although additive manufacturing techniques for ceramic matrix composites are evolving, their application has so far been largely limited to non-oxide systems such as SiC/SiC or C/SiC composites [63]. To date, no studies have demonstrated the use of additive manufacturing approaches to directly produce joined ox–ox CMC assemblies. As a result, additive manufacturing currently represents an open research opportunity rather than an established joining route for ox–ox CMCs, particularly for complex or large-scale components.

A key limitation in cross-study comparisons arises from the heterogeneity of joint configurations, test methods (e.g., single lap offset shear vs. flexural testing; flat vs. butt-joint geometries) and reported failure modes (interlayer cohesive failure, adhesive failure at the joining material/CMC interface or composite delamination). Therefore, the performance of each joining approach is discussed together with the dominant failure mechanism and the available durability evidence, rather than on the basis of strength values alone.

3.2.1. *Glass-ceramic systems to join ox-ox CMCs*

Over the past decades, glass-ceramics have emerged as one of the most extensively investigated joining materials for ceramic matrix composites due to their favorable combination of thermo-mechanical compatibility, oxidation resistance, and compositional flexibility. Compared with metallic brazing systems, glass-ceramic interlayers generally provide improved chemical compatibility with ox–ox CMCs and reduced thermal expansion mismatch, thereby limiting residual stress accumulation during thermal cycling and high-temperature exposure. In addition, their composition can be tailored to control crystallization behavior, viscosity, and thermal expansion, enabling the development of joining systems specifically optimized for long-term operation under extreme conditions and harsh operating environments [64]. In addition, glass-ceramics can be applied using relatively simple deposition techniques, such as slurry deposition, robocasting or screen printing, which facilitates their employment and has led to their increasing use in complex-shaped components and in advanced engineering applications, including solid oxide fuel cells and thermal barrier coatings.

A key advantage of glass-ceramic joining is the so-called glass-ceramic sinter-crystallization approach, which enables pressure-less joining and the fabrication of joints capable of withstanding harsh and high-temperature environments [65]. In this process, a parent glass softens during joining and subsequently crystallizes upon controlled heat treatment, resulting in glass-ceramic joints with improved thermo-mechanical stability. Moreover, their chemical composition and crystalline phases can be precisely tailored to ensure excellent thermal and chemical compatibility with the joined components, thereby minimizing residual stresses at the interface.

Beyond conventional joining applications, the glass-ceramic sinter–crystallization approach also enables the development of self-healing, radiation-resistant, and functionally graded joining materials, which are particularly attractive for applications in harsh environments such as aerospace propulsion systems and nuclear reactors [64].

Early studies mainly focused on silica-based glass-ceramic systems designed to provide adequate wetting and thermal compatibility with oxide composites. Gadelmeier et al. [66] investigated the joining of ox–ox CMCs, which consist of a zirconia matrix reinforced with Nextel 610™ fibers (3 M, Corporation, US), using commercially available glass sealants. The resulting joints exhibited a flexural strength of about 32 MPa, corresponding to roughly 13% of the flexural strength of the composite. In a subsequent study, the same research group explored the use of a SiO_2-CaO-Y_2O_3-based commercial glass sealant to join ox–ox CMCs, employing both furnace and CO_2 laser joining methods [67]. Furnace-joined specimens achieved flexural strengths of approximately 39 MPa, about 11% of the base composite strength (368 MPa), whereas

CO_2 laser-joined joints exhibited significantly lower strength (around 15 MPa) [67].

Another example of a glass-ceramic system used for joining ox–ox CMCs is the SiO_2-CaO-Al_2O_3-MgO-Y_2O_3-ZrO_2-based sealant (referred to as GOX), developed by M. Y. Akram et al. [50]. This sealant was specifically designed to join ox–ox CMC composed of Nextel™ 610 fibers with Al_2O_3-ZrO_2 (75 wt%−25 wt%) matrix. Typical joints obtained are reported in Fig. 4.

Joints fabricated using this glass-ceramic were tested through single lap offset shear tests, showing an apparent shear strength of approximately 7 MPa. Furthermore, four-point bending tests were carried out both at room temperature and at 850 °C, resulting in cohesive failure within the glass-ceramic and a flexural strength of 81 ± 5 MPa at 850 °C. To assess long-term mechanical stability of the joints, four-point bending creep tests were performed on CMC/GOX/CMC joints [68] for 50 h at 850 °C and 1000 °C under applied stresses corresponding to approximately 40–50% of the joint bending strength [68]. At 850 °C, the joined specimens did not exhibit any significant difference from unjoined CMCs (deflection < 7 μm), whereas at 1000°C a notable increase in deflection (> 50 μm) was observed in the joined CMCs, due to the mechanism of viscoelastic deformation of the GOX glass-ceramic.

Although GOX systems demonstrated promising thermo-mechanical compatibility, their relatively limited shear strength and viscoelastic deformation at elevated temperature highlighted the need for improved glass-ceramic formulations with enhanced interfacial stability and mechanical performance. M. Y. Akram et al. also developed a SiO_2-Al_2O_3-CaO-MgO-based sealant system called SACM that was used to join Nextel™ 610 fiber-reinforced YAG-ZrO_2 matrix composites, Fig. 5 [69].

The apparent shear strength of the joined CMCs measured by SLO test was 15 ± 1 MPa, with failure occurring within the composite, whose interlaminar shear strength was about 12 MPa, rather than at the joint interface. Furthermore, four-point bending tests yielded an average flexural strength of 68 ± 12 MPa, corresponding to approximately 35% of the flexural strength values of the base ox–ox CMC (198 MPa). Thermal ageing tests were performed in air at 850 °C and 930 °C for 100 h and 50 h in air, respectively. As shown in Fig. 6, after 50 h at 930 °C, the glass-ceramic/CMC interface remained well bonded, with no detectable discontinuities or cracks, or formation of reaction products.

Compared with the previously discussed GOX systems, SACM joints exhibited improved apparent shear strength and better interfacial stability after thermal ageing, indicating the beneficial effect of optimized glass composition and reduced thermo-mechanical mismatch. Subsequent developments focused on glass-ceramic systems specifically optimized for more severe thermal environments and direct flame exposure conditions. Promising glass-ceramic sealants, referred to as T1 and T2M, based on the SiO_2-Al_2O_3-TiO_2- Y_2O_3 system were developed for joining Nextel™ 610 fiber-reinforced Al_2O_3-ZrO_2 matrix composites intended for radiant tube components in the steelmaking industry [37]. In particular, the T1 glass-ceramic was originally developed by D'Isanto et al. as an oxidation protective coating for thermoelectric materials [70]. In terms of chemical composition, the two sealants are constituted by the same oxides, in different weight percentages so that T2M has lower characteristic temperatures compared to the T1 system (Table 1), and therefore the joining process can be performed at lower temperatures.

Both T1 and T2M exhibited low-porosity and homogeneous microstructures characterized by fine $Y_2Ti_2O_7$ crystals (~0.8–1 μm) dispersed within a residual amorphous matrix (Fig. 7). Additionally, infiltration of T1 and T2M into the ox–ox CMC is evident, as indicated by a dark contrast at the glass-ceramic/composite interface. Apparent shear strengths of 18 ± 5 MPa for the T1 joints and 12 ± 5 MPa for the T2M joints were measured by SLO tests. These values are comparable to the interlaminar strength of the composite (12 MPa) [37], with full delamination of the ox–ox CMC observed for the T1 joints after the SLO tests [37]. The joined specimens were also subjected to direct exposure to a C_2H_2/O_2 flame at 900 °C for 30 min, followed by thermal cycling between 400 °C and 900 °C. Neither the T1 nor the T2M joints broke during the tests and remained intact. T1 joints demonstrated excellent thermal cycling resistance, while T2M glass-ceramic joints showed the formation of a few vertical cracks in the glass-ceramic layer after flame

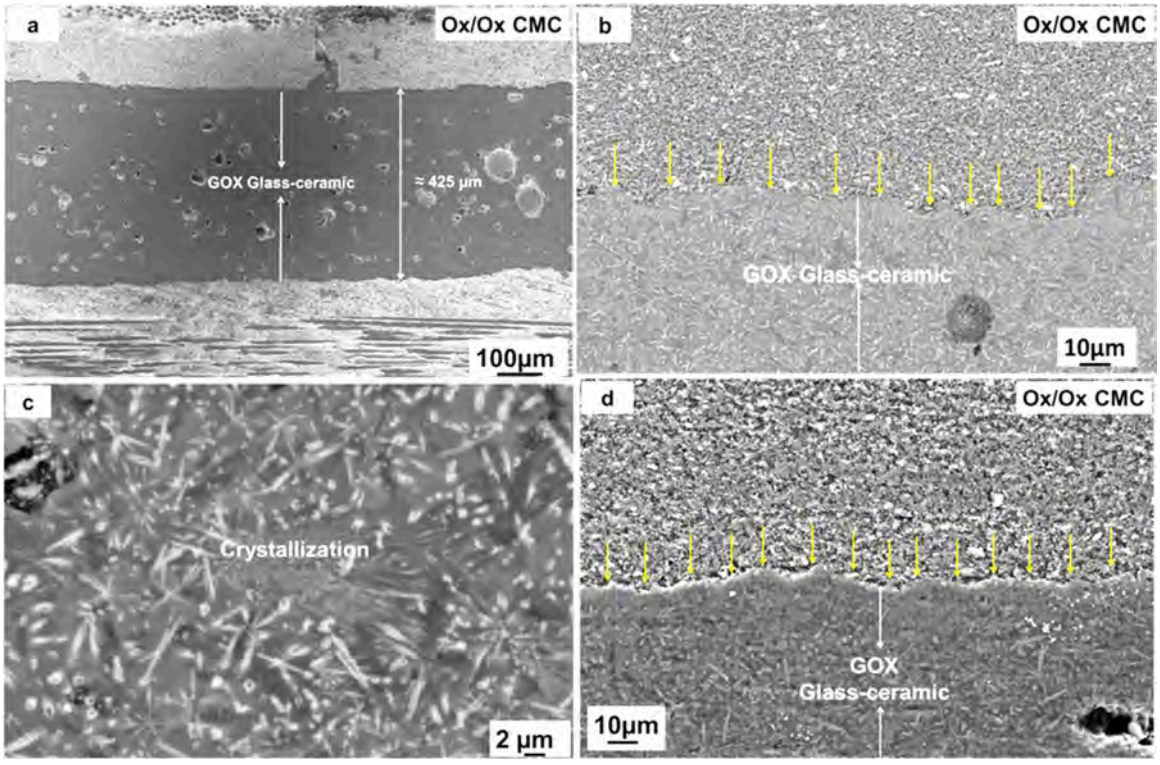

Fig. 4. Cross-sections of GOX joint and GOX glass-ceramic crystallization a) joint cross-section; b) joint cross-section in backscattered mode; c) crystalline phases (bright) in glass matrix (dark); d) joint cross-section after thermal ageing for 100 h at 850°C in air (from [50]).

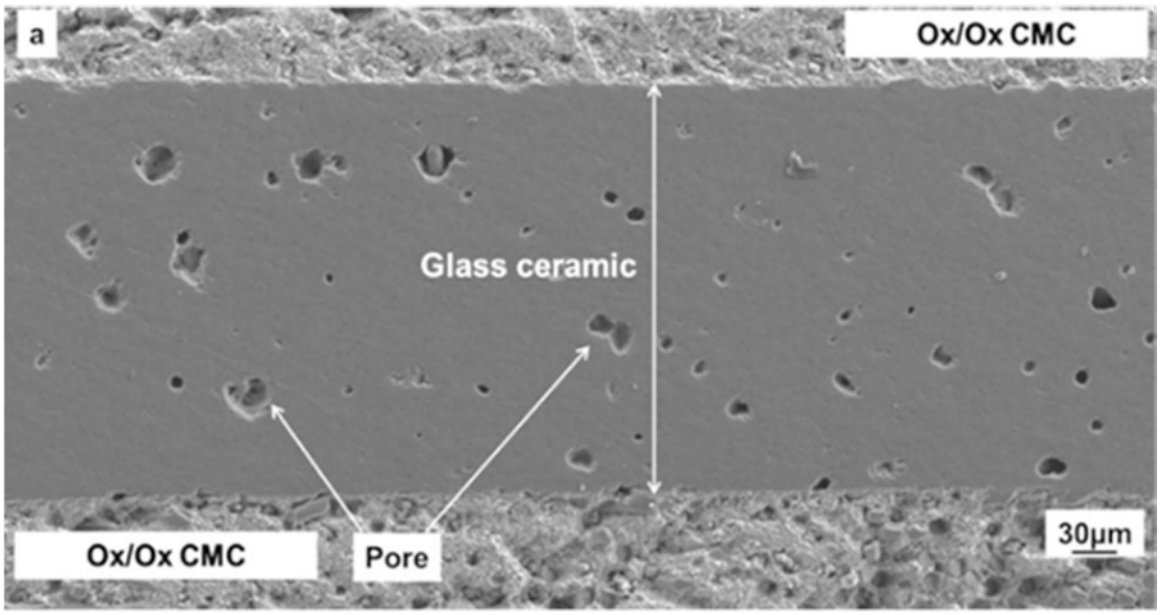

Fig. 5. SACM glass-ceramic joined ox-ox CMCs at 980 °C for 1 h (from [69]).

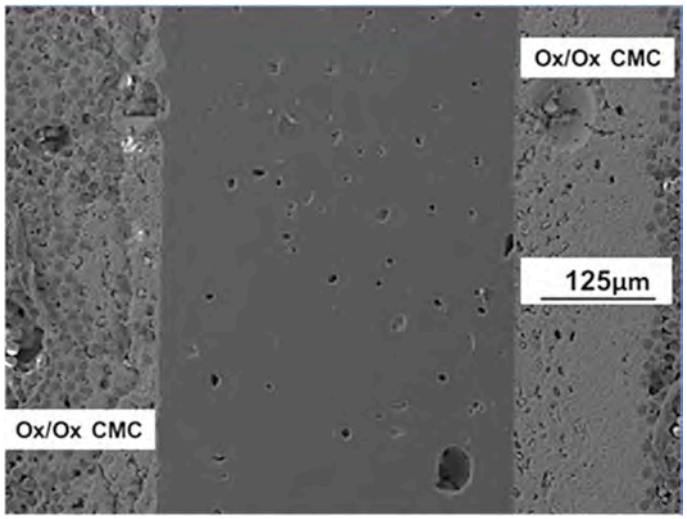

Fig. 6. Cross-section of SACM glass-ceramic joined Ox-Ox CMC after 50 h of thermal ageing at 930 °C in air (from [69]).

exposure, as reported in Fig. 8.

The different behaviors observed for T1 and T2M joints primarily originate from their differences in thermal expansion mismatch and their ability to relax stresses at high temperature (e.g. flame exposure). Depending on interlayer CTE, and the temperature-dependent modulus/viscosity, CTE mismatch can lead to tensile stresses that promote cracking within the glass-ceramic (e.g., vertical cracks within T2M after severe thermal gradients).

In contrast to GOX and SACM systems, T1 and T2M glass-ceramics were specifically designed for direct flame exposure applications, thus extending the potential operating window of glass-ceramic joined ox–ox CMC assemblies. Taken together, these studies illustrate the progressive optimization of glass-ceramic compositions toward higher joint strength, improved thermal durability, and operation under increasingly demanding service conditions.

Table 1 summarizes the different glass-ceramic systems used to join ox–ox CMCs in terms of chemical composition, mechanical properties, and maximum joining process temperatures [64].

Overall, the studies discussed above demonstrate a progressive evolution of glass-ceramic joining systems from conventional thermally compatible sealants toward more application-oriented interlayers capable of sustaining increasingly severe thermo-mechanical and environmental conditions. Glass-ceramic joining currently emerges as the most mature solution for ox–ox CMCs, supported by the largest and most consistent experimental database available in the literature. Optimized glass-ceramic systems have demonstrated promising combinations of thermo-mechanical compatibility, oxidation resistance, and thermal durability under ageing, thermal cycling, and direct flame exposure conditions. However, current studies also reveal important limitations, particularly related to time-dependent deformation, long-term creep resistance, cracking under severe thermal gradients, and the limited transferability of joining solutions across different composite architectures, including variations in fiber weave, volume fraction, and interface design. These aspects indicate that further composition tailoring, stress-management strategies, and long-term durability validation remain necessary for reliable industrial implementation of glass-ceramic joined ox–ox CMC assemblies.

Table 1
Summary of the glass-ceramic systems used to join ox-ox CMCs (* failure in the CMC, delamination).

Acronym	Composition (wt%)	Preparation Temperature (°C)	Joining Temperature (°C) ± 10	CTE Glass-ceramic ($\cdot 10^{-6}$ K^{-1})	Apparent Shear strength [MPa]	Reference
GOX	39.5 SiO_2 12.5 Al_2O_3 21.5 CaO 12.5 MgO 12.5 Y_2O_3 1.5 ZrO_2	1650	1010	8.93 (125°C–900°C)	7*	[50,68]
SACM	42 SiO_2 32 Al_2O_3 20 CaO 6 MgO	1600	980	7.40 (200°C–650°C)	15.4*	[69]
T1	30.91 SiO_2 20.60 Al_2O_3 20.60 TiO_2 15.46 Y_2O_3 5.15 CaO 5.15 Na_2O 2.13 K_2O	1650	1300	9.4 (200°C–500°C)	18*	[37]
T2M	30.91 SiO_2 20.60 Al_2O_3 15.60 TiO_2 11.70 Y_2O_3 9.53 CaO 2.13 Na_2O 9.53 K_2O	1650	1250	12.3 (200°C–500°C)	12	[37]

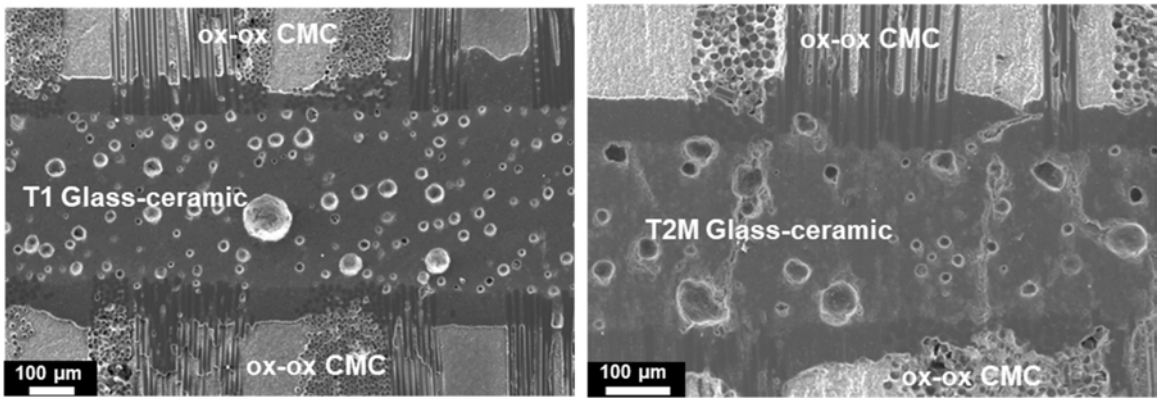

Fig. 7. Cross-sections of T1 (left) and T2M (right) glass-ceramics used to join ox-ox CMCs (from [37]).

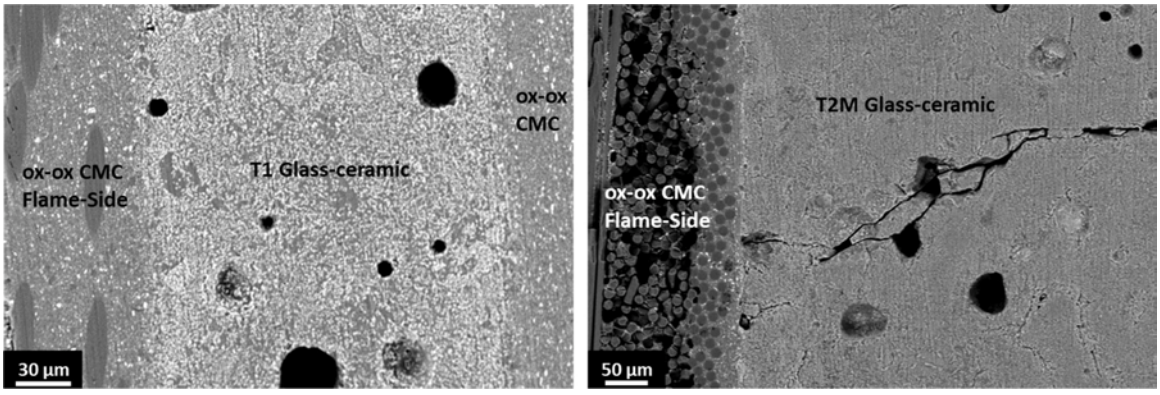

Fig. 8. Cross-sections of direct flame exposure tested T1 and T2M joints.

3.2.2. Brazing alloys for joining ox-ox CMCs

Brazing remains a highly effective technique for joining ceramics and ceramic matrix composites either to themselves or to metallic substrates, allowing the formation of strong, reliable joints at moderate to high temperatures. However, the inherent nature of ceramics, with their predominantly ionic and covalent bonding networks, presents significant challenges for brazing, particularly poor wettability of molten filler metals, and the development of high residual thermal stresses due to

thermal expansion mismatch. To overcome these issues, two primary strategies have been developed. The first is indirect (or passive) brazing, which involves metallizing the ceramic surface (e.g., via sputtering or electroless plating of a thin metal layer) and subsequently performing a conventional metal-to-metal braze. This approach has the benefit of transforming a ceramic-to-metal joint into a metal-to-metal joint, thereby improving wetting and lowering the entry barrier for standard filler alloys. The second is reactive (or active) brazing, in which the filler alloy contains small amounts of active elements, such as Ti, Zr, or Hf. These elements react with the ceramic surface to form a thin reaction layer of stable compounds (e.g., TiO_2, ZrC, Zr_2Si, etc.), thereby enhancing wettability and promoting metallurgical bonding at the interface.

Beyond interface chemistry, residual stress management remains a critical issue in brazed ceramic joints. Buffer layers, including soft metallic interlayers, compliant layers, or hybrid composites containing ceramic or metallic particles, are often introduced to tailor the effective CTE and reduce residual stresses. Finite-element modeling and experimental studies consistently demonstrate that joint performance is strongly influenced by careful joint design, interface reaction layer thickness, filler alloy selection, and CTE-gradient management. Altogether, while brazing ceramics and CMCs remains non-trivial, the combined advances in metallization, active filler alloys, and stress-relief strategies have significantly expanded the range of viable ceramic-metal and ceramic-ceramic assemblies for demanding structural applications [71–73].

The addition of Ti into brazing alloys is widely used to improve the wettability on oxide-based ceramics and ox–ox CMCs by reducing interfacial energy and promoting chemical reactions at the interface. As an example, AgCuTi, AgCuSnTi, ZrNiTiHf, and metallic foils with the sequence Ti/Cu/Al/Cu/Ti (TiCuAl) have been investigated for vacuum brazing of ox–ox CMCs composed of a YAG/ZrO_2 matrix reinforced with Nextel™ 610 fibers [69]. In all cases, continuous interfaces between the filler and the composite were observed, regardless of fiber orientation (Fig. 9).

Mechanical SLO testing revealed apparent shear strengths in the range of 2–5 MPa. Cohesive failure was observed only in ZrNiTiHf-joined samples, whereas adhesive failure occurred in all other cases. Thermal ageing tests conducted at 550 °C in air for 1 h showed that Ti/Cu/Al/Cu/Ti brazed joints remained intact, while joints produced with the other brazing alloys showed partial or complete debonding.

More recently, Malinverni et al. investigated the use of a titanium-based high-entropy alloy (tradename TiBraze200Nb) to join ox–ox CMCs. Two joint configurations were evaluated: flat and butt geometries [74]. A comprehensive description of the preparation for flat and butt configuration joints is shown in Fig. 10.

Butt-joints exhibited markedly higher shear strength (49 MPa), compared with flat-joints (4 MPa), primarily due to improved infiltration of the alloy into the composite and bonding between the alloy and the ceramic fibers. Beyond infiltration and load transfer, the butt-like configurations (Fig. 11) also reduce peel stresses and convert part of the thermally induced mismatch into more favorable stress states, lowering crack-opening driving forces at the ceramic/interlayer interface during cool-down and cycling. These results clearly demonstrate that joint geometry can be as important as filler selection in determining brazed joint performance.

To simulate the behavior of the brazing material in a combustion environment, TiBraze200Nb-brazed joints were exposed to an acetylenic oxy-fuel flame with a stoichiometric composition at 900 °C. The butt joints remained intact after exposure, indicating that TiBraze200Nb is a highly effective brazing alloy for joining ox–ox CMCs for application in harsh environments. Table 2 summarizes the cited metallic brazing systems used to join ox–ox CMCs.

Overall, brazing can deliver outstanding apparent joint strength, but only under carefully optimized conditions where joint geometry, infiltration quality, and thermal-stress management are simultaneously addressed. However, the strong dependence on joint geometry and the limited long-term oxidation data remain key limitations for the use of metallic fillers in ox–ox CMC assemblies. As a result, brazing represents a high-potential but still high-risk joining strategy for ox–ox CMCs,

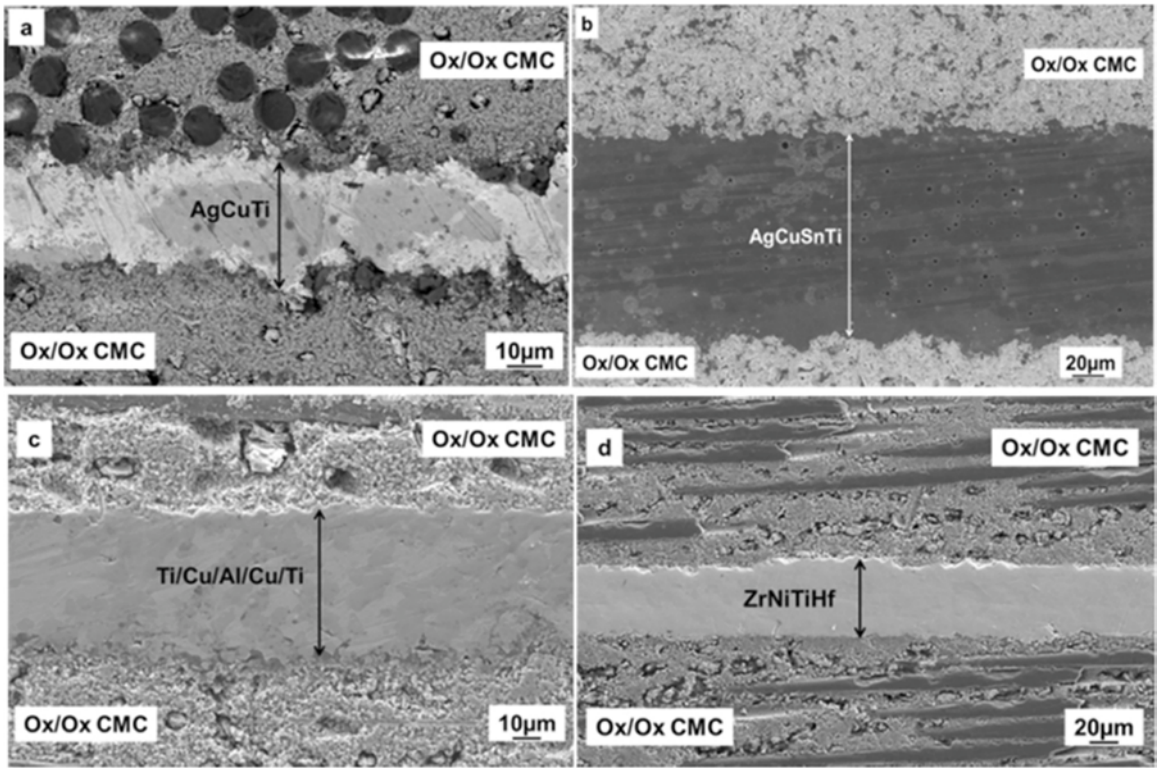

Fig. 9. Cross-sections of ox-ox CMC joined by using commercial and new brazing materials (a) AgCuTi (b)AgCuSnTi (c) the new TiCuAl and (d) ZrNiTiHf (from [69]).

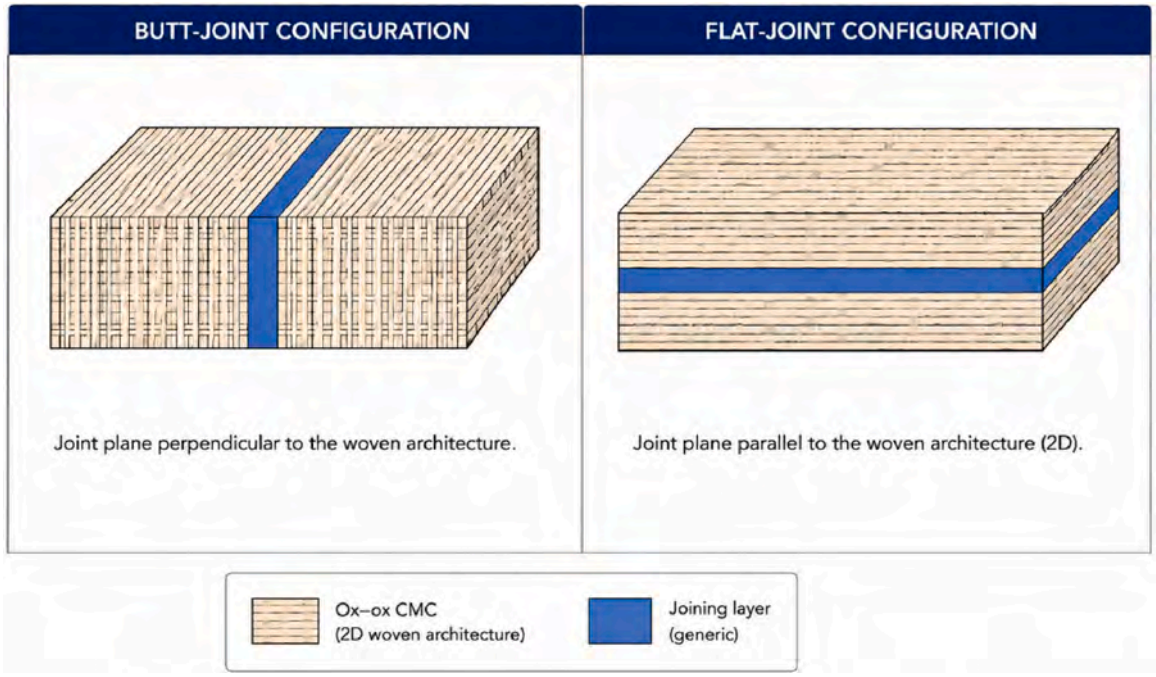

Fig. 10. Schematic representation of flat and butt-joint configurations.

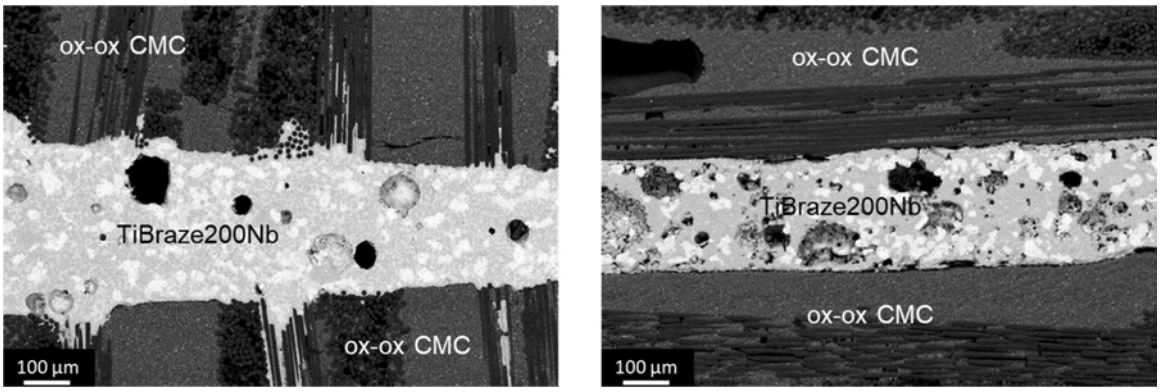

Fig. 11. Cross-sections of ox-ox CMCs joined using brazing alloy TiBraze200Nb in butt (left) and flat (right) configurations.

Table 2
Summary of the properties of brazing alloy systems to braze ox-ox CMCs.

Acronym	Composition (wt%)	Brazing Temperature (°C) ± 10	CTE at RT ($\cdot 10^{-6}$ K^{-1})	Apparent shear strength (MPa)	Reference
CusilABA	Ag−35.25Cu−1.75Ti	850	18.5	Ranging between 2 and 5	[69]
TKC651	Ag−28Cu−5Sn−2Ti	900	19.7		
TiBraze590	Zr−17.3Ti−20Ni−1Hf	920	8.8		
TiCuAl (Ti/Cu/Al/Cu/Ti)	Cu−11.7Ti−8.2Al	1100	-		
TiBraze200Nb	Ti−17Zr−17Cu−17Ni−17Nb	1050	-	Flat-joint: 4 Butt-joint: 49	[74]

requiring further durability-focused investigation.

3.2.3. Adhesives for joining ox-ox CMCs

Because adhesives have intrinsically lower temperature stability compared to the high temperature operating requirements of CMCs, only a few studies have investigated adhesive joining of CMCs, and even fewer specifically address ox–ox CMCs.

Almeida et al. [75] explored a new method for joining ox–ox CMCs based on the gelation of slurries with the polysaccharide polymer alginate. This technique, called ionotropic gelation, uses a natural polymer called alginate (derived from seaweed) that forms a gel when it reacts with certain metal ions (e.g. Al^{3+}). This gel can be used to bond ceramic components together before they are consolidated (sintered). Ox–ox CMC plates were joined with the ionotropic gelation method during different stages of composite processing: when the composite is in the wet-gel state (gel joint), after drying (green joint), and after sintering (sintering joint). When joining was performed in the gel or green state, the joints were almost indistinguishable from the surrounding composite (Fig. 12).

The shear strength of these joints was comparable to the interlaminar

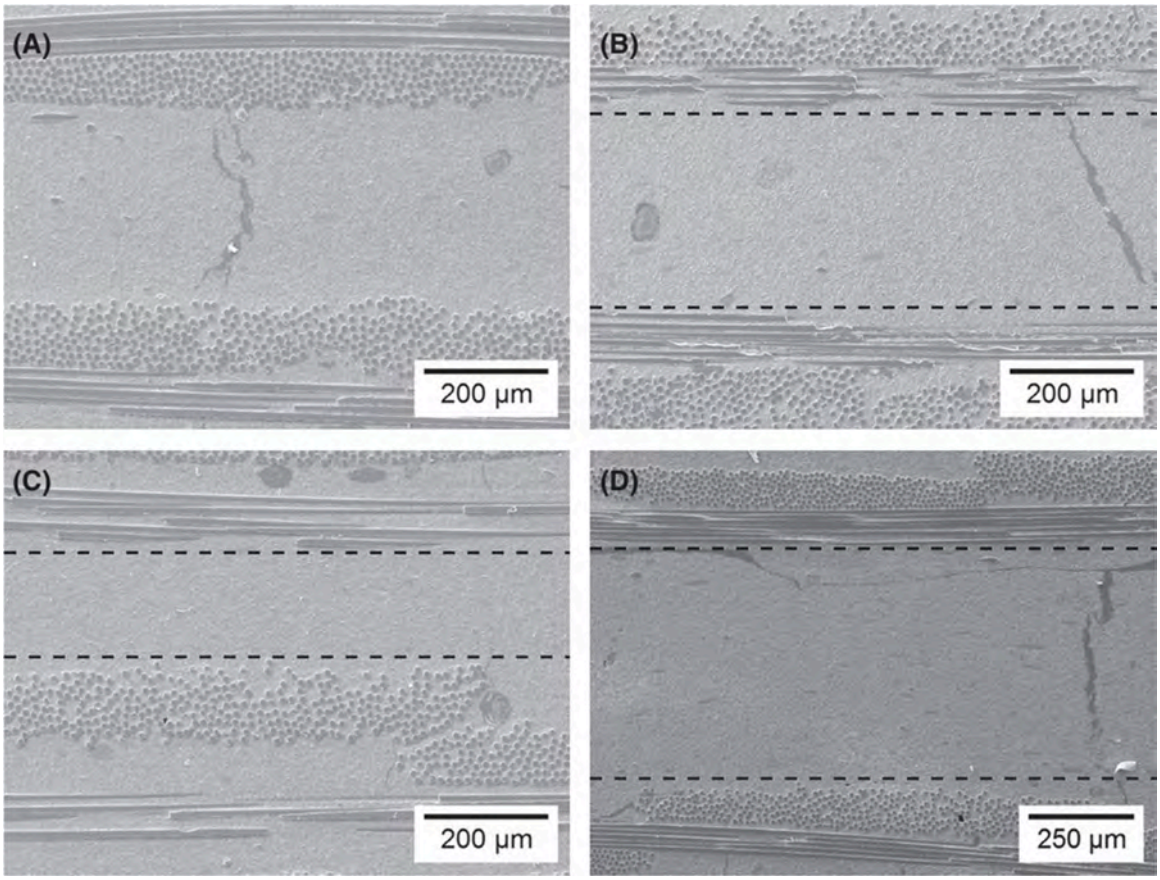

Fig. 12. Cross-sections of N610/AZ composites produced (A) and joining area of gel joint (B), green joint (C), and sintering joint (D). Dashed lines demarcate the joining region (from [75]).

shear strength of the composite itself (7.8 ± 0.5 MPa). In contrast, joints produced after sintering showed extensive cracking within the joint region and significantly reduced shear strength (0.8 ± 0.2 MPa). In conclusion, the study demonstrated that ionotropic gelation is a promising method for joining ox–ox CMCs, provided it is performed before final sintering. This technique offers a simple and cost-effective alternative to traditional high-temperature joining methods, such as brazing or glass-ceramic bonding, while avoiding some of the compatibility issues these methods typically face.

From a critical perspective, adhesive-based approaches should be regarded primarily as manufacturing-stage or processing-aid solutions rather than viable stand-alone joining methods for high-temperature service, given the pronounced strength degradation observed after final sintering or thermal exposure.

3.2.4. *Mechanical joints for ox-ox CMCs*

Mechanical joining, typically achieved using bolts or rivets, is a widely adopted method for assembling CMCs [46]. It offers several advantages, including structural robustness, reversibility, and ease of disassembly, which are particularly beneficial for maintenance and modular system design. However, this approach also introduces drawbacks, such as additional weight, the need for drilling operations that may damage brittle ceramic substrates, and increased manufacturing costs. Although mechanically fastened joints can sustain high mechanical loads, their performance at elevated temperatures may degrade significantly mainly at the contact/interface region between the fastening hardware (bolts, nuts, washers, or inserts) and the ox–ox CMC [76]. While extensive literature exists on mechanical joining of non-oxide CMCs, particularly C- or SiC-fiber reinforced composites, studies specifically addressing mechanical joints in ox–ox CMCs remain scarce, highlighting a significant knowledge gap [77]. Bouillon et al. investigated the mechanical behavior of bolted joints in ox–ox CMCs composed of alumina fiber-reinforced alumina with a porous matrix [76]. Their study focused on how damage develops under bearing loads, revealing failure modes such as fiber buckling, matrix cracking, delamination, and the formation of shear bands.

An example of mechanical integration of ox–ox CMCs into metallic structures is provided by the HiPOC program, which focused on the development of innovative joining solutions for ox–ox CMCs in gas turbine engines [78]. In this program, joining concepts were specifically designed to accommodate thermal expansion differences and to minimize mechanical residual stress. Flexible metallic brackets and leaf springs were used to allow radial and axial displacement, while Inconel bolts combined with conical washers ensured secure fastening under high temperatures. This approach enabled reliable integration of ox–ox CMC components into gas turbine combustors.

Mechanical fastening offers clear advantages in terms of reversibility and integration flexibility. However, its high temperature performance in ox–ox CMCs remains largely design-dependent and insufficiently quantified. The scarcity of ox–ox CMCs specific datasets limits the development of robust engineering guidelines, underscoring the need for standardized high-temperature testing and damage-mechanism-oriented design concepts for mechanically joined ox–ox CMC assemblies.

3.2.5. *Comparative analysis of joining methods for ox-ox CMCs*

Table 3 provides a comparative overview of the performance and applicability of joining methods for ox–ox CMCs (from the studies cited in the previous paragraphs). In particular, the table summarizes key parameters and outcomes reported in the literature, including joining

Table 3
Comparative performance of the different joining methods for ox-ox CMCs.

Joining route	**Joining material** [reference]	**Joining process T [°C]**	Max demonstrated thermal exposure / service T	Mechanical test set-up	Joint strength and configuration	Thermal stability evidence	Oxidation / environment evidence	**Key limitations / applicability**
Glass-ceramic bonding	GOX [50,68]	~1010	Creep tested 50 h at 850 °C and 1000 °C	SLO shear test: 15 mm × 4 mm × 2 mm (joining area: 32–36 mm^2); Four-point bending: 45 mm × 4 mm × 2 mm [46] Creep tests: 50 mm × 4.2 mm × 2.2 mm [64]	Shear ≈ 7 MPa (flat); flexural 81.5 ± 5.5 MPa at 850 °C	At 850 °C: deflection < 7 μm; at 1000 °C: deflection > 50 μm (viscoelastic deformation)	Ageing in air reported (microstructural continuity)	Good high-T compatibility, but creep/viscous flow can limit the upper-T window
Glass-ceramic bonding	SACM [69]	~980	Thermal ageing in air 850°C/ 100 h and 930°C/50 h	SLO shear test: 13 mm × 4 mm × 2 mm (joining area: 36–40 mm^2); Four-point bending: 50 mm × 6 mm × 2 mm (joining area: 12 mm^2)	Shear 15.4 ± 1.2 MPa (flat); flexural 68.5 ± 12.1 MPa	Interface remained well bonded after 930 °C ageing, no cracks /reaction products	Air ageing at high T reported	Promising for 900 °C-class use; strength still below base composite flexural strength
Glass-ceramic bonding	T1 / T2M [37]	~1250–1300	Direct flame exposure 900 °C/30 min + thermal cycling 400–900 °C	SLO shear test: 15 mm × 10 mm × 3 mm (joining area: 70–75 mm^2)	Shear 18 ± 5 MPa (T1, flat); 12 ± 5 MPa (T2M, flat)	T1 excellent thermal cycling resistance; T2M shows vertical cracks after flame exposure	Explicit flame + cycling tests reported	Strong evidence for harsh environments; damage (cracking/delamination) must be discussed as design constraint
Brazing (active fillers)	AgCuTi / AgCuSnTi / ZrNiTiHf / TiCuAl [69]	850–1100	Ageing at 550 °C/1 h (TiCuAl survived; others debonded)	SLO shear test: 13 mm × 4 mm × 2 mm (joining area: 36–48 mm^2)	Shear 2–5 MPa (Ag-based, flat)	Limited high-T durability dataset in current ox-ox literature	Oxidation sensitivity of metallic fillers should be emphasized	Often lower shear than target; oxidation + CTE mismatch risks; still relevant for CMC-to-metal or specific architectures
Brazing (Ti-based HEA)	TiBraze 200 Nb [74]	~1050	Flame exposure at 900 °C (butt joints intact)	SLO shear test: flat joining area: 100 mm^2, butt joining area: 30 mm^2	Shear 49 MPa (butt) vs 4 MPa (flat)	Shows strong geometry dependence; highlight design sensitivity	Flame test suggests environmental robustness (short-term)	Best-in-class strength when joint design promotes infiltration; needs more long-term oxidation/ creep data
Adhesive/ processing-aid joining	Ionotropic gelation (alginate) [75]	Low-T gelation; final joining occurs pre-sintering	No high-T joint testing reported (method is effective before final sintering)	SL compression shear tests: 20 mm × 10 mm. Joint length: 7.9 ± 0.8 mm, joining area: 80 mm^2	Shear 7.8 ± 0.5 MPa (gel/green); 0.8 ± 0.2 MPa if attempted after sintering	Not assessed vs ageing/ cycling in cited study	Adhesives generally limited for high-T use	Useful for manufacturing/repair routes; not a stand-alone high-T joining solution unless joint becomes fully ceramic after processing
Mechanical fastening	Bolts/rivets; HiPOC concept [76]	Ambient assembly	Elevated-T performance can degrade (thermal mismatch, stress concentration); ox-ox data scarce	-	Quantitative joint strength rarely reported for ox-ox	Damage modes under bearing loads reported (matrix cracking, delamination, etc.)	Depends on metal hardware oxidation/ creep; design-specific	Best for maintainability/ modularity; usually needs compliant concepts (springs/ brackets)

process temperatures, specimen size and configuration, mechanical test setups, and the resulting mechanical performance and thermal stability of the joints.

The comparative trends summarized in Table 3 and schematically illustrated in Fig. 2 indicate that glass-ceramic joining currently provides the most balanced combination of thermal stability, oxidation resistance, and environmental durability for ox–ox CMC applications, as demonstrated by the available thermal ageing, flame exposure, and thermal cycling datasets. For example, SACM-based joints remained stable after exposure at 930 °C, while T1 and T2M joined ox–ox CMCs survived direct flame exposure and thermal cycling. These results indicate that glass-ceramic interlayers can deliver reliable performance under harsh thermo-mechanical conditions when their composition and thermo-viscoelastic response are appropriately tailored.

In contrast, brazing can deliver very high apparent shear strength when joint geometry promotes effective filler infiltration and favorable load transfer, as demonstrated by butt-joints produced using TiBraze200Nb. However, long-term oxidation/chemical stability of metallic fillers remains critical in ox–ox CMC assemblies.

A recurring observation across the different joining routes is that failure during shear testing often occurs by delamination or damage within the composite rather than purely cohesive failure in the joining materials. This behavior indicates that, in several cases, the apparent joint strength is governed by the interlaminar shear strength of the composite itself, rather than by the intrinsic strength of the joining material. Consequently, joint performance is controlled not only by the properties of the interlayer, but also by composite architecture, interlaminar toughness, and joint design parameters that influence stress distribution and load transfer across the interface.

Brittle interlayers or insufficient stress relaxation tend to promote cracking within the interlayer and/or at the composite/interlayer interface, whereas more compliant or viscous glass-ceramic systems can partially relax thermal stresses, shifting failure toward composite-dominated delamination under shear loading.

In brazed joints, the dominant failure mode is strongly influenced by joint geometry and braze infiltration quality: flat or poorly infiltrated joints typically fail by interfacial debonding at the composite/metal interface, whereas butt or scarf-like configurations favor cohesive failure within the filler or damage propagation into the composite, resulting in higher apparent joint strength. These experimental observations highlight the critical role of joint design in controlling stress distribution and crack-opening driving forces.

Adhesive-based or processing-stage joining routes generally exhibit failure dictated by the weakest stage of the composite consolidation, with cracks initiating in poorly densified regions or at green-state interfaces, leading to composite-dominated failure rather than true interfacial debonding. Finally, mechanically fastened joints in ox–ox CMCs show characteristic bearing-induced damage, including matrix cracking, fiber buckling, delamination, and shear band formation, with failure propagation controlled by local stress concentrations around the fastener.

Overall, these observations indicate that joint failure in ox–ox CMC assemblies is rarely governed solely by the intrinsic strength of the joining material. Instead, failure initiation and propagation are largely dictated by the combined effects of thermal mismatch, joint geometry, interlayer compliance, and load transfer mechanisms. An integrated consideration of these factors is therefore essential for the design of robust joints capable of sustaining reliable high-temperature service.

3.2.6. *Evaluation of the mechanical strength of ox-ox CMC joints*

Among the available methodologies for the mechanical characterization of ceramic joints, asymmetric four-point bending (A4PB), standardized in ASTM C1469, is currently the only standardized test method specifically developed for determining the shear strength of joints of advanced ceramics and CMCs [79]. Although the method provides a more controlled stress state than conventional lap-shear configurations, finite-element analyses have demonstrated that the shear stress distribution within the joint is not perfectly uniform [80]. Furthermore, its practical application presents several limitations; in particular, the feasibility of this method depends on the flexural strength ratio between the joined material and the substrate, which may restrict its use for high-strength joints.

Obtaining a reliable measure of the intrinsic shear strength of joined specimens, unaffected by secondary stress components and stress concentrations, remains a long-standing challenge in joint characterization. This limitation is also acknowledged in several lap-shear standards developed for adhesive joints [81,82], where the measured values are reported as apparent shear strength rather than intrinsic interfacial shear strength. Therefore, results from lap tests should, in general, be used only for comparative purposes and not to evaluate the shear strength for design purposes. To mitigate some of the limitations of conventional lap-shear tests, modified configurations such as the single-lap offset test have been developed and extensively applied to oxide–oxide CMC joints. A particular type of lap shear test is the SLO test in compression (Fig. 13), a modification of the ASTM D905 (designed for wood substrates) in which, together with thick and stiff substrates, ad hoc fixtures are adopted to keep these substrates as parallel as possible during the test to minimize peel stress due to rotation and/or bending of the substrates [80,83]. The fixture shown in Fig. 13 was specifically designed to minimize adherend rotation and bending, thereby promoting a more uniform shear stress distribution and reducing peel stresses. In addition, this test configuration was used to assess both similar and dissimilar joints, including metal/CMC joints.

Ferraris et al. [83] showed that the compression SLO configuration significantly mitigates the common limitations affecting conventional lap-joint configurations, such as non uniform stress–strain distribution with peaks in the ends of the overlap, and the presence of peel stress due to the possible non-alignment of the adherends and their bending deformability. The two joined adherends were relatively thick and short, thus their bending was minimized. Moreover, the fixture kept the specimen aligned during the test by means of a roller supporting its back face; therefore, a nearly uniform relative sliding of the adherends was obtained during this test.

One of the principal advantages of the single-lap offset shear method is that it allows direct comparison between different joining techniques and processing conditions.

The methodologies adopted in Refs. [37,50,68,69,74,75] summarized in Table 3 show substantial variability in specimen geometry, overlap configuration, loading mode, and gripping systems, which currently limits direct comparison between datasets reported in the literature. As a consequence, the apparent shear strength values reported throughout this review should be compared with caution, particularly when different overlap geometries, specimen dimensions, and loading fixtures are employed.

Based on the currently available literature, ASTM C1469 remains the most rigorous standardized methodology for determining the intrinsic shear strength of ceramic joints. However, its application to oxide–oxide CMC systems remains limited. Conversely, the single-lap offset configuration has become the most widely adopted method for ox–ox CMC joints due to its experimental simplicity, reduced material consumption, suitability for high-temperature testing, and ability to provide reproducible comparative data. Consequently, the apparent shear strength values reported in the literature should primarily be interpreted as comparative indicators of joint performance rather than absolute material properties. The establishment of a dedicated testing standard specifically addressing the architecture, anisotropy, and failure mechanisms of ox–ox CMC joints could improve the reproducibility and comparability of experimental results, facilitating the development and qualification of reliable joining technologies for high-temperature structural applications.

Finally, Fig. 14 provides a comparative overview of the main joining routes currently explored for ox–ox ceramic matrix composites,

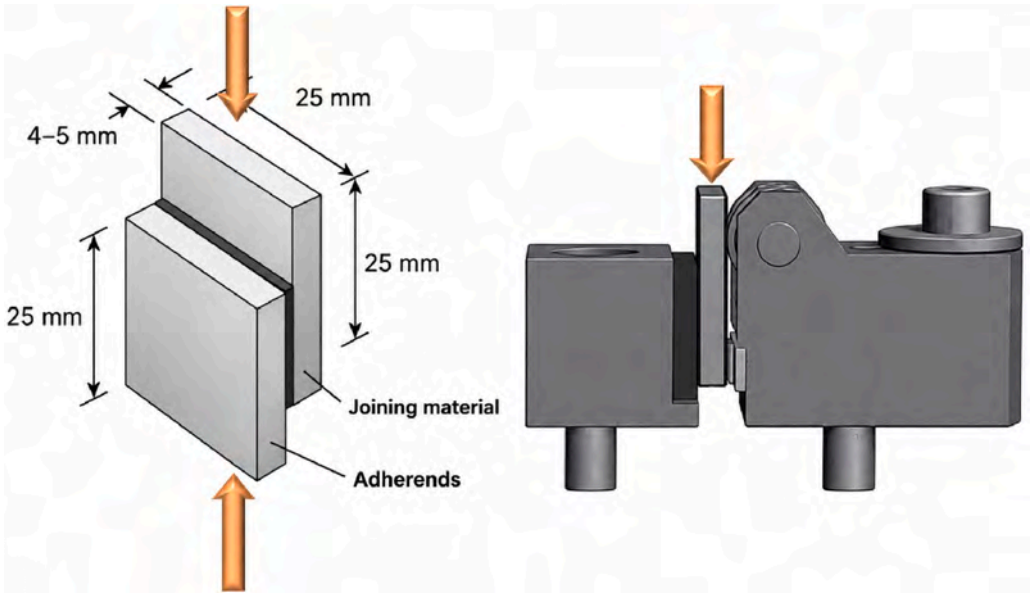

Fig. 13. Sample setup and fixtures to avoid bending and rotation of the adherends in the SLO test [adapted from [83]].

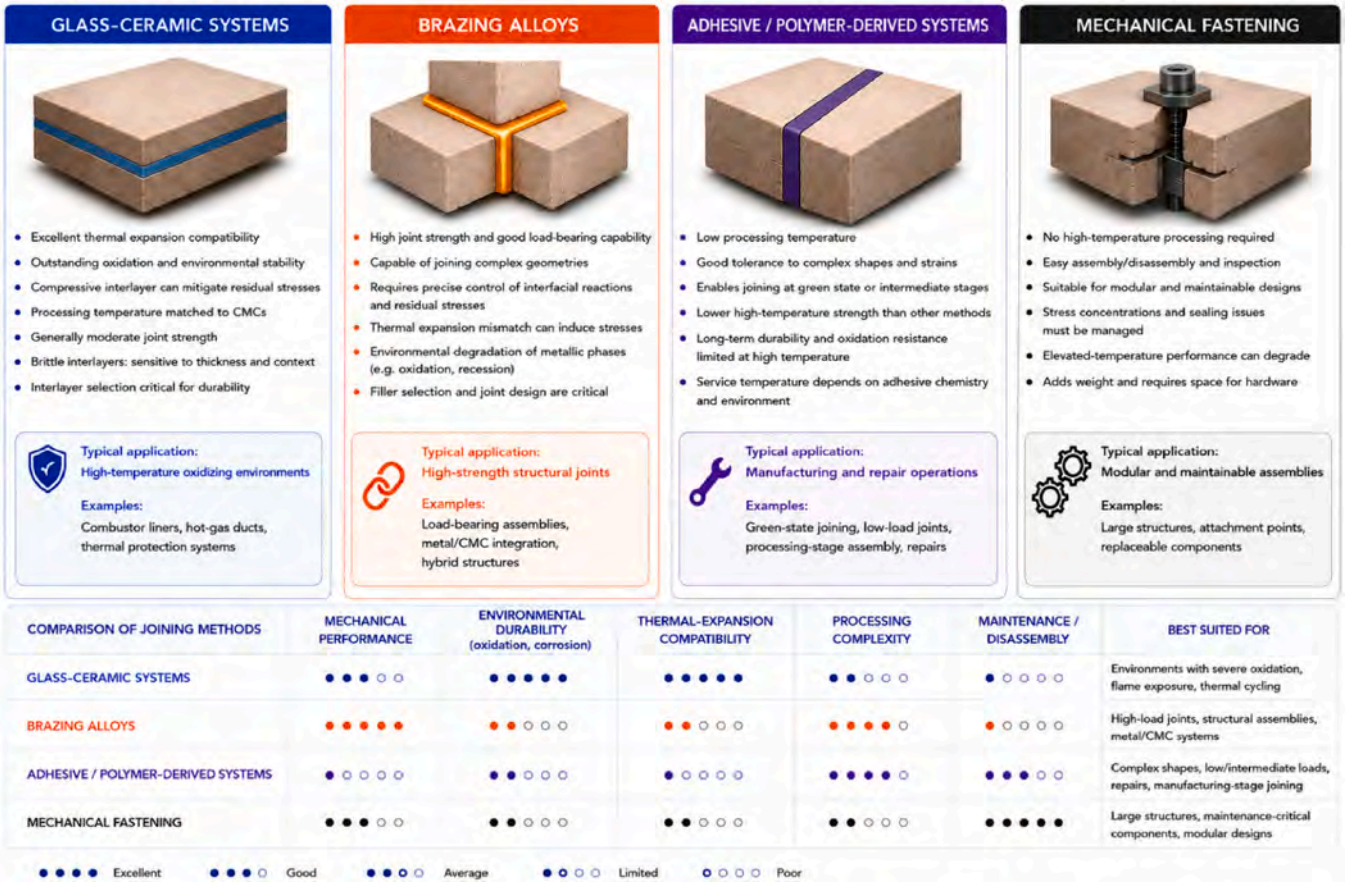

Fig. 14. Comparative overview of the principal joining approaches for oxide–oxide ceramic matrix composites (ox–ox CMCs), highlighting their relative advantages, limitations, thermo-mechanical compatibility, environmental durability, processing complexity, and typical application scenarios.

including glass-ceramic, brazing alloys, adhesive systems, mechanical fastening, and hybrid joining approaches.

4. Summary and outlook

This review has critically examined the current state of research on joining technologies for oxide–oxide ceramic matrix composites, highlighting both the significant progress achieved and the major scientific

and technological challenges that still limit their broader industrial implementation. Ox–ox CMCs are increasingly considered for high-temperature aerospace, energy, and industrial applications due to their low density, oxidation resistance, and thermo-mechanical stability under severe service conditions. However, the integration of these materials into large and complex assemblies remains strongly dependent on the availability of reliable joining technologies capable of maintaining structural integrity during long-term thermal and mechanical exposure.

The comparative analysis of the currently available joining routes indicates that glass-ceramic systems presently provide the most balanced combination of thermo-mechanical compatibility, oxidation resistance, and environmental durability for ox–ox CMC applications. In particular, glass-ceramic joints based on SiO_2-$Al2O_3$-CaO-MgO and SiO_2-$Al2O_3$-TiO_2-$Y2O_3$ systems demonstrated apparent shear strengths ranging from approximately 12–18 MPa, together with stable behavior after thermal ageing at temperatures up to 930 °C and direct flame exposure at 900 °C. These values are comparable to, and in some cases exceed, the interlaminar shear strength reported for several ox–ox CMC systems, indicating effective load transfer and good interface integrity. Nevertheless, glass-ceramic joining remains sensitive to viscous deformation, thermal cycling damage, and local cracking associated with thermal gradients and stress relaxation phenomena.

Brazing approaches can achieve significantly higher apparent joint strengths, particularly when optimized joint geometries promote effective filler infiltration and favorable stress redistribution. For example, Ti-based brazed joints with optimized geometry exhibited apparent shear strengths approaching 49 MPa. However, metallic brazing systems remain potentially vulnerable to CTE mismatch and long-term oxidation-related degradation, for which only limited durability data are currently available. Adhesive and gel-assisted joining approaches offer promising low-temperature and manufacturing-stage solutions, but their application in structural high-temperature environments remains limited. Mechanical fastening provides advantages in terms of modularity and maintainability, although stress concentrations, local damage accumulation, and limited high-temperature datasets still restrict its widespread application in ox–ox CMC assemblies.

A recurring observation across the different joining technologies is that joint failure frequently occurs within the composite rather than within the joining layer itself. This indicates that the overall joint performance is not governed solely by the intrinsic strength of the joining material, but rather by the complex interaction among composite architecture, interfacial stress distribution, thermal expansion mismatch, interlayer compliance, and joint geometry. Consequently, reliable joint design requires an integrated approach combining materials development, interface engineering, thermo-mechanical modelling, and structural optimization.

Despite the encouraging progress achieved in recent years, several critical challenges remain open. One of the main limitations is the absence of testing methodologies specifically developed and widely adopted for ox–ox CMC joints. Although ASTM C1469 provides a standardized methodology for advanced ceramic joints, its application to ox–ox CMC systems remains limited. In addition, long-term durability data under realistic operating conditions, including creep, thermal cycling, flame exposure, steam environments, and oxidation-assisted degradation, remain relatively scarce. Future research should therefore increasingly focus on durability-driven design strategies and on the correlation between microstructural evolution and failure mechanisms during service.

Particularly promising future directions include the development of functionally graded and hybrid joining interlayers aimed at reducing thermal stresses while maintaining adequate mechanical performance at elevated temperatures. Advanced oxide-based composite interlayers, compliant multi-layer architectures, and hybrid joining concepts represent promising research directions for improving damage tolerance and environmental stability. Furthermore, the integration of computational modelling approaches, including finite-element thermo-mechanical simulations and multiscale damage models, together with advanced in situ characterization techniques, will be essential for predicting residual stresses, optimizing joint geometry, and accelerating material selection and process design.

Finally, although additive manufacturing technologies for ceramic matrix composites are rapidly evolving, their application to joining and repair of ox–ox CMC structures remains largely unexplored. This area represents a particularly attractive opportunity for the development of next-generation integrated joining concepts for complex and multifunctional high-temperature structures. Overall, coordinated advances in joining materials, interface design, durability assessment, and modelling methodologies will be essential to enable the transition of ox–ox CMC joining technologies from laboratory-scale demonstrations to reliable industrial implementation.

CRediT authorship contribution statement

Valentina Casalegno: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Carla Malinverni:** Writing – original draft, Investigation, Conceptualization. **Milena Salvo:** Writing – review & editing, Validation, Supervision. **Fabiana D'Isanto:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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