ADVANCED MANUFACTURING ROUTES FOR METAL/COMPOSITE COMPONENTS FOR AEROSPACE

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Abstract

The aim of ADMACOM (Advanced manufacturing routes for metal/composite components for aerospace) project is to develop innovative manufacturing technologies based on advanced design of interfaces and of joining materials for aerospace components. Innovative joining technology for Ceramics and Ceramic Matrix Composites (CMC) to metals for aerospace components will be developed. The combination of advanced design of interfaces and joining materials/technologies, selective matrix removal from the composite surface, laser structuring and mechanical machining of the composite/metal surface will be exploited.

1. Introduction

Manufacturing technology based on joining is a critical tool for reducing assembly time, cost and excessive use of materials.

A strong EU expertise in joining is particularly needed for the new type of Ceramic Matrix Composites (CMC) produced in EU which have to be implemented in the dominant field of metals, for optimisation of existing components, but also for new products and new design solutions due to the need of reducing fuel costs and environmental pollution [1, 2]. The current drive is to combine dissimilar materials and processes in "hybrid" structures to permit the best properties of each material to be used and hybrid structures employing dissimilar materials are deeply dependent on joining technologies.

An extensive research on brazing of ceramics and CMC for their joining and integration has been done by M. Singh and his group at NASA [3, 4]. More specifically, the use of SiC based ceramic, in form of both bulk and composites (SiC/SiC or C/SiC) for aerospace demands attention. These materials have no melting phase, therefore it is impossible to join them by conventional fusion welding and diffusion bonding does not seem suitable as the inter-diffusion of SiC is very low, even at high temperature. Several joining techniques have been investigated for SiC ceramics by liquid joining media, also through a transient liquid phase [5]. At the same time, studies on reactive [7, 8] and non-reactive [9, 10] wetting of metallic alloys on an SiC substrate were investigated.

Even if there are several well-known joining methods, they are usually not completely satisfactory for joining of dissimilar materials [11, 12] .
Conventional joining methods such as brazing or diffusion bonding are suitable for many metals and ceramics; however, severe drawbacks are encountered when designing joining processes for high-temperature applications. When a liquid phase is used that is solidified by cooling, joining temperatures exceed the ultimate use temperature of the assembly. These high temperatures can lead to either degradation of the ceramic phase or interfacial reactions that form brittle interfacial layers. Transient Liquid Phase Bonding (TLPB) is a technique well developed for joining metals but still to be fully explored for ceramics: since it introduces a liquid phase at relatively low temperatures, these drawbacks can be bypassed.
Solid-state processes require high temperatures and high pressures to get sufficient mass transport; in addition, the surfaces to be joined must be meticulously prepared in order to minimize flaws or voids which could act as strength-limiting defects after processing.

Advances in brazing have been recently reviewed in [13]. Brazing is the most commonly used joining and integration method for ceramics and CMC; copper, nickel and silver are the most frequently-used base metals for brazing alloys; aluminum and gold are also used for specific purposes. For each base metal, many different alloy compositions are available. The additional metals combined with the base metal determine the brazing alloy compatibility for use in joining specific substrate. High temperature brazing alloys are based on gold, nickel and copper and are often used for joining ceramics and CMC to cobalt or nickel-based superalloys [14]. Selecting the optimal braze filler metal for brazing CMC to metals is not easy because, since the application can require a high brazing temperature (high thermal load in operation predicted), the prevention of high joining stresses should require a low brazing temperature. Moreover, the wetting of ceramics and CMC requires often active metal elements but in order to avoid intermetallic phases the absence of brittle phase forming elements is mandatory. Besides, in order to deal with the CTE mismatch between ceramics and brazing alloys, several options have been proposed: different layers with a gradually changing CTE from CMC to the brazing alloy, compliant metallic layers (e.g. Cu), stiff layers (e.g. W, Mo), composite brazing alloys obtained by adding short fibers or particles to the brazing alloy matrix [15, 16].

Airbus group (formerly EADS) and MT Aerospace have embarked on a considerable work over the past eight years on novel manufacturing technologies based on joining; their expertize is within an area that this project can bring advances and innovation: e.g. EADS developed and worked on brazing technology for C/SiC to metal joining developed for orbital propulsion systems, such as small thrusters for satellites , as well as on laser structuring of all types of ceramic and CMC surfaces. The SiCBraze technology was developed in order to join C/SiC (SiCARBON^{TM}) combustion chambers with a metallic niobium ring/flange which is necessary for clamping the injection head of the satellite thruster. Main joining steps were laser structuring of the C/SiC surface, cleaning and metallization of the structured C/SiC surface and brazing of the CMC material to the niobium alloy part.

The aim of this work is to report on novel manufacturing technologies based on joining of ceramics and CMC: e.g. optimized mechanical/laser working on surfaces to be joined, selective matrix removal from CMC surface to obtain the brush-like joints and newly designed joining materials and interfaces such as high temperature resistant graded brazing alloys.
All this will allow the joining of smaller segments, which can help to enlarge shape and dimension without increasing the mass, without additional fastening elements and without the

risk of fasteners loss/damage, combined with the aspect of saving overall space and increasing the flexibility in design.
Considering a typical ceramic fastener/nut combination weights around 50-100 g/piece, it can be applied as a redundant way to ensure safety and structural integrity, only if necessary.

2. Experimental part

2.1 Joining by Spark Plasma Sintering (SPS)
CVD-SiC coated C/SiC composites used in this study were manufactured in disk shaped samples with diameter of 20 mm and height of 5 mm by MT Aerospace (Germany).
C/SiC were joined by SPS technique (SPS-FCT 1020, Germany) using joining materials or by direct bonding. Specimens joined by direct bonding were hand polished up to 3 µm diamond slurry in order to reduce roughness and maximize the contact surface.
The as received samples were ultrasonically cleaned in acetone. Before inserting the samples in a 2 cm^2 graphite mould an interlayer was interposed between the materials to be joined. The temperature was probed by an optical pyrometer installed on the top side of the SPS machine. The following joining materials were used:
Titanium: Ti joined C/SiC were produced using Ti foils of 30 and 130 µm thickness.C/SiC-Ti-C/SiC sandwiches were heated by SPS between 150 and 200°C/min, with a dwell time of 3 minutes and a pressure of 60 MPa in vacuum atmosphere. The maximum temperature was set at 1700°C.

Direct bonding (DB) of C/SiC (without joining materials in between) has been also obtained by SPS; this techniques requires high temperature and high pressure : the SPS parameters were set at 1900°C and 60MPa.

2.2 Pressure-less joining of CMC
C/SiC and SiC/SiC composites were joined using $CaO–Al_2O_3$ (49.7 CaO, 50.3 Al_2O_3 wt%) glass-ceramic, which is referred to as CA here forth. The joining material was designed, prepared, and characterized as described in [17]. CA joined samples were obtained by depositing a CA slurry (i.e. a mixture of as-cast CA powder, grain size 38–75 microns, and ethanol) at room temperature between the two parts of CMC.
Sandwich-like joined samples were heated in a tubular furnace to 1480°C for 10 minutes, with a minimal pressure (a 25 g tungsten disk was put on the top to keep samples in place) in an argon atmosphere.

Polished cross sections were analysed by scanning electron microscopy equipped with Energy Dispersive X-ray Spectroscopy (SEM - FEI, QUANTA INSPECT 200, EDS - EDAX PV 9900) and by Field Emission Scanning Electron Microscopy FESEM (Supra 40, Zeiss, Germany) and micro X-ray diffraction (Rigaku D/MAX Rapid microdiffractometer, X-ray generator settings fixed at 40 kV and 20 mA, Cu Ka incident radiation with λ=1.54 Å) with a spot detector of 30μm^2.

3. Results and discussion

Titanium was chosen as a joining material for C/SiC composites because of its refractory properties, well know reactivity with SiC and good bonding effects at SiC –Ti interface.
Figure 1 shows the polished cross-sections of C/SiC specimens joined by using Ti foil as joining material, while Figure 2 shows the polished cross-sections of C/SiC specimens joined by direct bonding (DB) through SPS technique. Cracks in the CVD-SiC coating are visible in

all joined samples and are due to the thermal expansion coefficient mismatch between SiC coating and C/SiC substrate. Figure 1 shows the cross-section of C/SiC joined by a 130 µm thick Ti foil. The cracks in the CVD-SiC coating did not propagate in the dense and pore-free joint area.
The interface CVD–SiC/titanium based joint is dense and defect free; moreover, micro-XRD analysis on the fracture surface (not reported here) indicated that Ti_3SiC_2 is formed at the interface. EDS element maps showed the formation of a titanium carbide at the centre of the joints, while a silicon rich phase (probably $TiSi_2$) was also detected in the joint region, but only in case of 130 µm thick titanium foil as joining material. Detailed discussion on reaction products at C/SiC –Ti interface is reported in [18].
A preliminary mechanical characterization has been given in ref [18] .
The apparent shear strength of C/SiC joined by a 30 µm thick Ti foil is 17 ± 7.8 MPa and about 20 MPa for the 130 µm thick foil. These values are comparable to the apparent shear strength obtained by testing the not joined C/SiC after heat treatment at 1700°C, 3 min,60 MPa, the same one used as joining treatment for C/SiC -Ti joints.

The choice of a $CaO–Al_2O_3$ glass–ceramic as joining material have been discussed in [19]; CA was designed to have a suitable wettability and CTE towards SiC based materials: CTE of CA glass ceramic is 5.2 10^{-6} °C^{-1} and its softening temperature is around 1380°C.
Moreover, it can be almost completely crystallized after a pressure-less joining process, thus leading to a potential high temperature resistant joining material.
C/SiC joined by CA glass-ceramic (Figure 3) in a conventional furnace (1480°C, 10 min, *no pressure*) showed a homogenous joint area without cracks. The thickness of the joint is homogeneous along the cross-section; the interface between the glass-ceramic and the composite is continuous and independent from fibres orientation (parallel or perpendicular to the surface); moreover it follows the morphology of the composite surface

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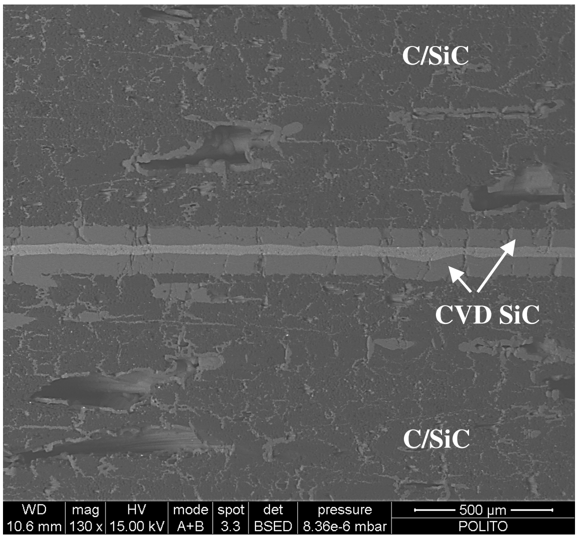

Figure 1. Scanning electron microscopy of polished cross-section of C/SiC specimen joined by SPS using a Ti foil of 130µm

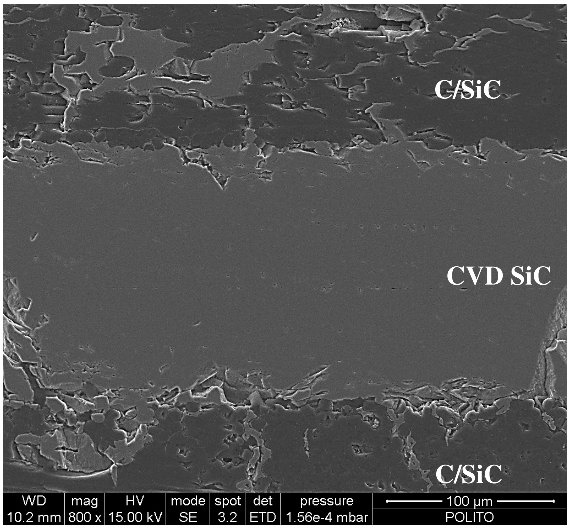

Figure 2. Scanning electron microscopy of polished cross-section of C/SiC specimen joined by SPS through direct bonding; the joints were processed at 60 MPa, 1900°C, 3min

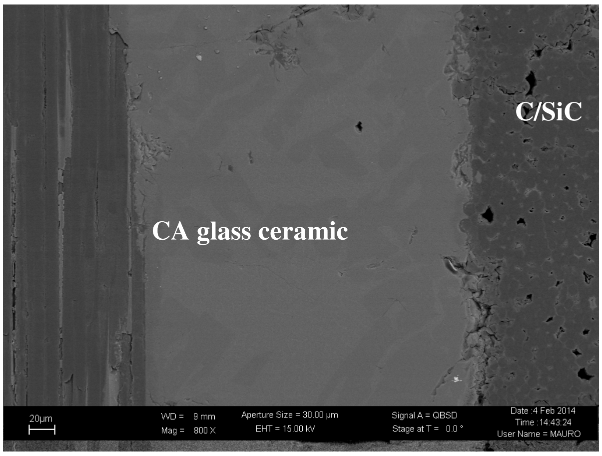

Figure 3. FESEM image of the cross section of CA-joined C/SiC

4. Conclusions

In this paper the concept behind the project ADMACOM has been described by different examples: the novel, reliable and efficient joining of dissimilar materials is a powerful manufacturing tool for enabling a speedy drive towards innovation and efficiency of several key EU industrial products, such as new composite materials for aerospace, one of the main EU leading commercial sectors.

SPS was successfully used to join C/SiC with and without joining materials. The main advantage of SPS technique consists in the rapid heating rate and a shorter dwelling time (3 minutes) in comparison with conventional heating (typically 30-60 minutes).

Moreover, a calcia–alumina glass is proposed to join C/SiC composites; the wettability and adhesion of the glass were very good on the C/SiC substrate. The joining process at 1480°C leads to a glass–ceramic joining material, which is thermomechanically compatible with the composites to be joined.

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