MULTIFUNCTIONAL FIBRE-REINFORCED METAL MATRIX COMPOSITES WITH INTEGRATED OPTICAL FIBRE SENSORS

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ABSTRACT

Increasing interest in fibre and textile reinforced composites urges the development and utilisation of innovative reliable structures capable of working in demanding complex loading conditions. However, the failure mechanisms of metal matrix composites have not been thoroughly investigated and require the exact monitoring of its internal structure. To fulfil these requirements the development of multifunctional Metal Matrix Composites (MMC) with embedded sensors for Structural Health Monitoring (SHM) is indispensable.

The embedding of optical fibres in the internal structure of Metal Matrix Composites using casting processes is hampered by extremely demanding manufacturing conditions and therefore has not been elaborated until now. High temperatures, pressures and influence of alloy elements on the structure of optical fibres are only a few obstacles that must be reduced or omitted in order to receive multifunctional MMC with embedded Fibre Optic Sensors (FOS).

This paper contains thermogravimetry analysis of optical fibres, elaboration of protective/adhesive Al_2O_3 coating using a sol-gel method and preliminary finite element analysis of thermal residual stresses formed during manufacturing processes as well as microscopic analysis of infiltrated optical fibres. These results contribute to the understanding of phenomena occurring during the embedding of optical fibres in aluminium alloy via demanding casting techniques. The embedding has been performed by infiltration of carbon fibre reinforced metal matrix composites with optical fibres via Gas Pressure Infiltration technique.

1. INTRODUCTION

Rising demands for energy efficiency in the fields of mobility and mechanical engineering lead to increasing the interest in metal matrix composites (MMC) reinforced by continuous carbon fibres and textiles. However, the failure mechanisms of MMC have not been thoroughly investigated and thus the prediction of damage conditions and lifetime is hampered. To meet the demand on safety relevant structures the self-monitoring of materials with integrated sensors and actuators is indispensable.

The development of smart materials opens up new opportunities to construct a multifunctional composite with embedded sensors. This leads to advanced material functionality without deterioration of mechanical properties and increasing of mass. Very good examples of SHM by implemented intelligent materials in the load-bearing structure of composite are optical fibres, where numerous methods of integration in fibre reinforced polymer composites can be found in literature [1–5]. However, the embedding of sensors and actuators in composites with metal matrices is hampered by the demanding conditions of their manufacturing processes. High temperature, high pressure and only a few developed integration methods of smart materials into the metal structure cause that production of multifunctional metal matrix composites has not yet been sufficiently developed.

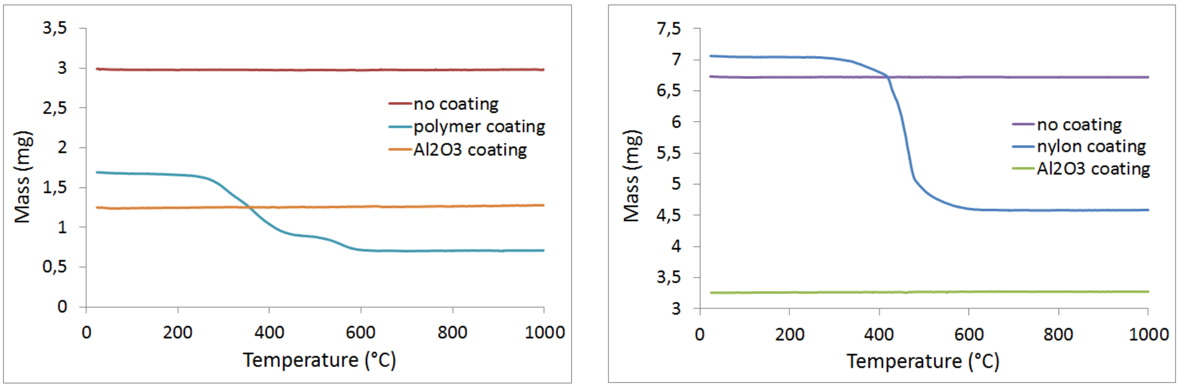
Good infiltration, proper arrangement of sensors, advantageous adhesion between matrix and fibre, chemical stability in contact with melted alloy and the capability of maintaining the optical characteristic after the manufacturing process are the main conditions in order to receive a high functionality and quality of product [5, 6]. To assess the applicability of selected fibre the thermal analysis and sol-gel coating have been performed. The paper contains a preliminary FE analysis of residual stresses induced by mismatch of thermal expansion coefficients between the aluminium alloy or the aluminium matrix composite and an optical fibre. Subsequently, based on the received results of analyses, the integration of optical fibre in aluminium alloy by GPI process has been performed. The results of preliminary integrations are shown by the help of scanning electron microscopy.

2. THERMAL ANALYSIS

For embedding into metal matrix composites the coating of optical fibres has to be characterised by stability above the temperature of manufacturing process as well as by the sufficient chemical resistance, or proper and predictable behaviour in contact with alloy. Industrially manufactured polymer coatings as well as rare and expensive metal coatings are often inappropriate for application in metal forming and casting industry [2, 7, 8].

Also the chemical and thermal stability of core and cladding of the optical fibre is a vital aspect for further MMC applications. Most common industrially manufactured fibres are made of silica which should be stable to 900 °C. However, the demanding manufacturing conditions and contact with matrix alloy can cause the degradation of the cladding and core of the fibre leading in consequence to destruction of their basic premise – transferring the light [9].

To confirm the thermal stability of optical fibres and coating as well as to estimate the temperature of optical fibre desizing process the thermogravimetry (TGA) has been done by the help of TGA/DSC1 analyser from Mettler Toledo GmbH. For this investigation two types of material have been tested: optical fibres made out of fused silica with germanium doped core (Corning® Single-mode Optical Fibre ITU-T G.652.D) as well as quartz optical fibres (CeramOptec® UV 300/330 BN). The analysis covered fibres without coating, with industrial polymer coating and fibres with sol-gel coating. Results are shown in the Figure 1. The temperature range of TGA tests exceeds 1000 °C which is 300 °C above the temperature of the infiltration process. The heating rate was 10 K/min.



a) b)

Figure 1: Optical fibres thermogravimetry: a) Silica Single-mode Optical Fibre ITU-T G.652.D; b) Quartz UV 300/330 BN.

The analysis has shown that optical fibres without coating as well as Al_2O_3 sol gel coated specimens do not show any mass loss within the temperature. This fact proves the thermal stability of optical fibres in the infiltration temperature range.

3. COATING METHOD

The sol-gel process is a simply method which leads to obtain oxide matrix, e.g. thin films, via hydrolysis and condensation reactions. The scheme of process is presented at Figure 2 [10].

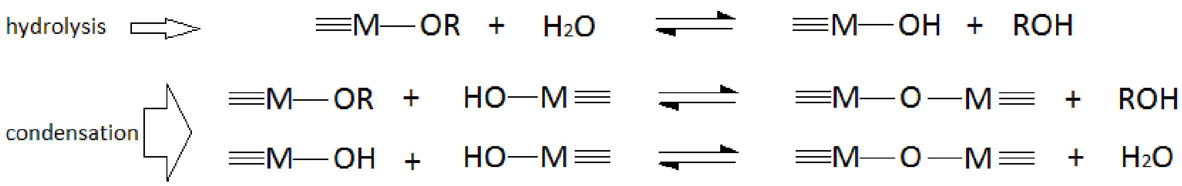


Figure 2: Schematic hydrolysis and condensation reactions, where: M - a metal atom and R - an alkyl group

In this work the coatings deposited on optical fibres were synthesised by the hydrolysis and condensations of aluminium isopropoxide (AliP, Alfa Aesar) solution in isopropanol (iPropOH, Stanlab) catalysed with nitric acid (HNO_3 Chempur) and using the dip-coating process. The deposition process (Figure 3) relied on the slow immersion and emersion of substrate in sol, wherein the speeds of each step were controlled. After the coatings drying, the thermal stabilization was carried out in 850°C with a specified temperature regime.

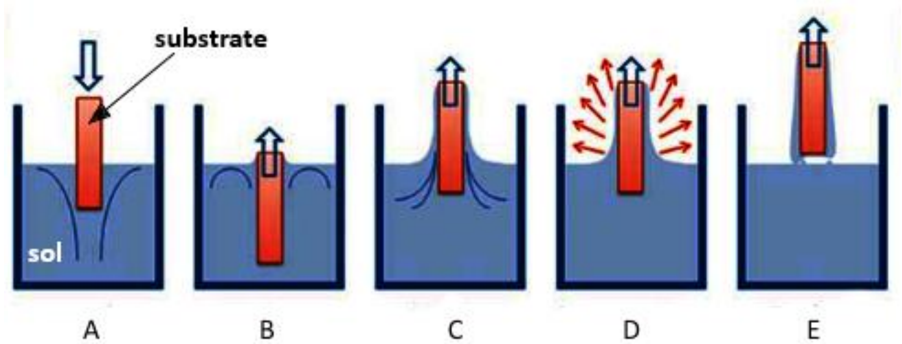


Figure 3: The dip-coating process, which consists of following steps: immersion (A), start-up (B), deposition and drainage (C-E), evaporation (D-E) (Figure prepared on the basis of H.K. Raut [11])

4. FINITE ELEMENT ANALYSIS OF THERMAL RESIDUAL STRESSES

Mismatch of thermal expansion coefficient between embedded fibre optic sensor and aluminium alloy contributes to damage of the optical fibre and loss of its light transmission capabilities. To estimate residual stresses caused in the process of embedding the FE analysis on a representative volume element has been done using ANSYS. Boundary conditions have been composed of cyclic symmetries and a transversal symmetry. The radius of created model of optical fibre was 62,5 µm what refers directly to the radius of optical fibre after removal of polymer coatings. The radius and the height of the representative volume element were 200 µm (Fig. 4) [12–16].

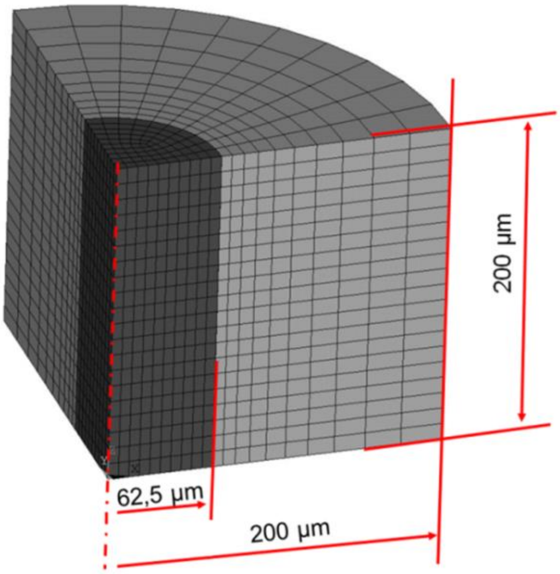


Figure 4: Representative volume element

The temperature set for numerical analysis has been determined regarding to characteristics of the alloy and its processing parameters used for embedding. It has been designated to the temperature at which solidification starts – liquidus temperature point of the alloy – equal to 600 °C [17]. For the purpose of numerical analyses it has been assumed that all material properties are constant and independent of temperature [17, 18]. The material properties used in FE analysis are shown in Table 1. The analysis reveals the von Mises stress and the equivalent strain formed in representative volume element by temperature difference between 600 °C and ambient temperature (Fig. 5).

	SI - Unit	Carbon Fibre (HM40J)	239 D alloy	HM-CF/226D
Young's modulus *(longitudinal)*	GPa	377	75	226
Young's modulus *(transversal)*		10		17,6
Shear modulus *(in axis)*	GPa	17	28,4	21,3
Shear modulus *(in plane)*				7,6
Poisson's ratio *(longitudinal)*	-	0,09	0,32	0,14
Poisson's ratio *(transversal)*		0,25		0,16
CTE *(longitudinal)*	$10^{-6}K^{-1}$	-0,83	21	10
CTE *(transversal)*		8		14,5

Table 1. Mechanical properties of selected materials

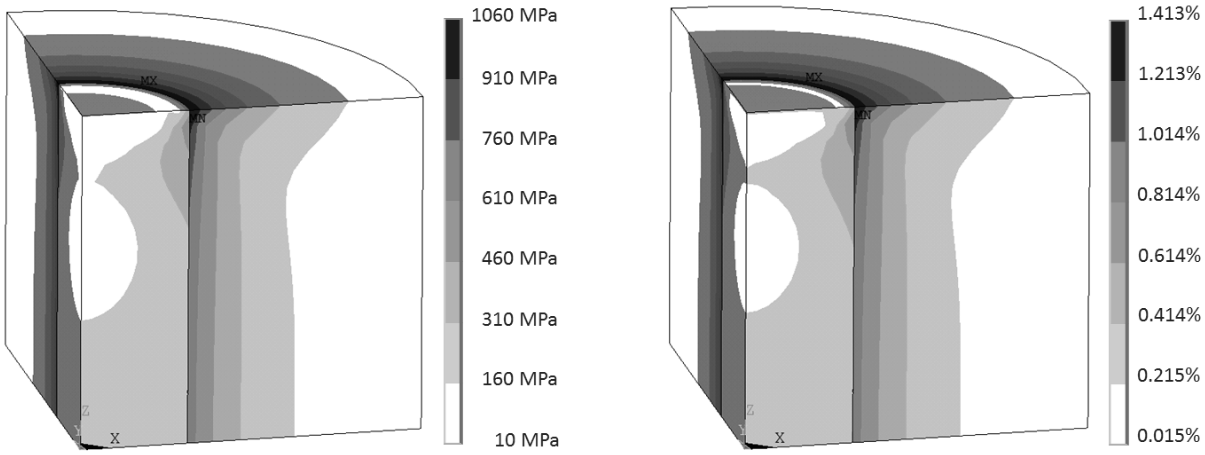


Figure 5: Stress and strain analysis of optical fibre embedded into 226D aluminium alloy: a) von Mises stress; b) equivalent strain

The results present the situation occurring on the surface of alloy where the optical fibre protrude beyond the specimen. On this surface the highest stress – of about 1000 MPa – is cumulated. In non-transient area the stress on the optical fibre is about 600 MPa. These stresses are caused by mismatch o thermal expansion coefficients and contribute to the destruction of the optical fibre hampering its application as a temperature and strain sensor.

To estimate the influence of carbon fibres on the reduction of destructive residual stresses an additional FEA of optical fibre embedded in aluminium matrix composite has been done. In this case carbon fibres have been placed along the optical fibre what decreases the coefficient of thermal expansion of aluminium alloy. Results of the simulation are shown in Figure 6.

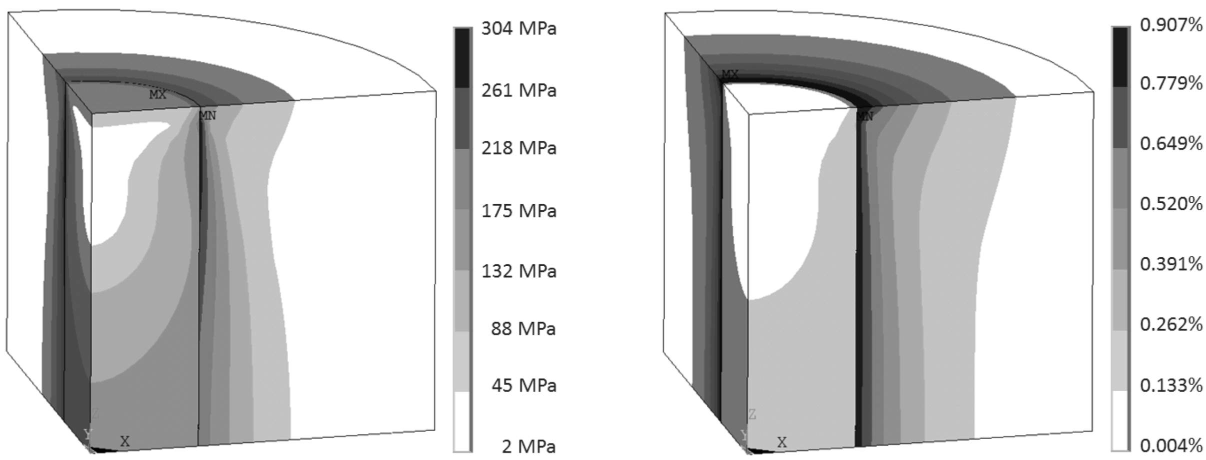


Figure 6: Stress and strain analysis of optical fibre embedded into 226D aluminium alloy reinforced by carbon fibre (HM40J): a) von Mises stress; b) equivalent strain

The maximum stress on the surface where optical fibre protrudes beyond the solidifying alloy is 304 MPa and it is 750 MPa lower than the stresses occurring by embedding of fibre optic sensor in unreinforced alloy. In non-transient area maximum stress is about 200 MPa. This fact reveals that the application of carbon fibres along the optical fibre directly contributes to the reduction of the thermal residual stresses formed during the embedding of fibre optic sensors via casting process.

5. GAS PRESSURE INFILTRATION

The infiltration of optical fibre by Gas Pressure Infiltration (GPI) technique has been done based on results received from Finite Element Analysis. The specimen has been prepared using 239D aluminium alloy and 50% of carbon fibre volume fraction with positioned optical fibres. The infiltration of specimen has been performed using argon inert gas. The infiltration temperature was 720 °C and the infiltration pressure was 10 MPa. The scheme of GPI process and graph of temperature-pressure-time of the process have been shown in Figures 7 and 8. Advanced Gas Pressure Infiltration process is a technique used at ILK, TU Dresden with a laboratory autoclave (Fig. 7) and is described as a favourable method for manufacturing of metal matrix composites reinforced by continuous fibres. The process is able to provide the control of two temperatures (lower heater and upper heater) of the mould as well as the pressure of inert gas and the vacuum applied to the infiltration chamber. Moreover, the laboratory autoclave provides the measurement of four temperatures (upper heater, lower heater, melt area and specimen area) as well as partial pressure and high pressure what gives the advantage to fully control the parameters of infiltration and predict its results [4–6].

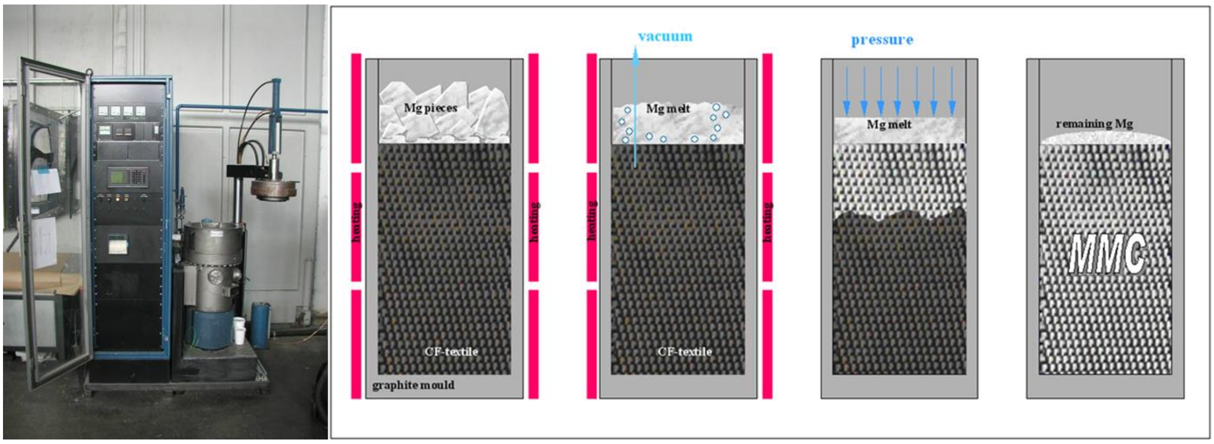


Figure 7: Laboratory autoclave and representative scheme of GPI process.

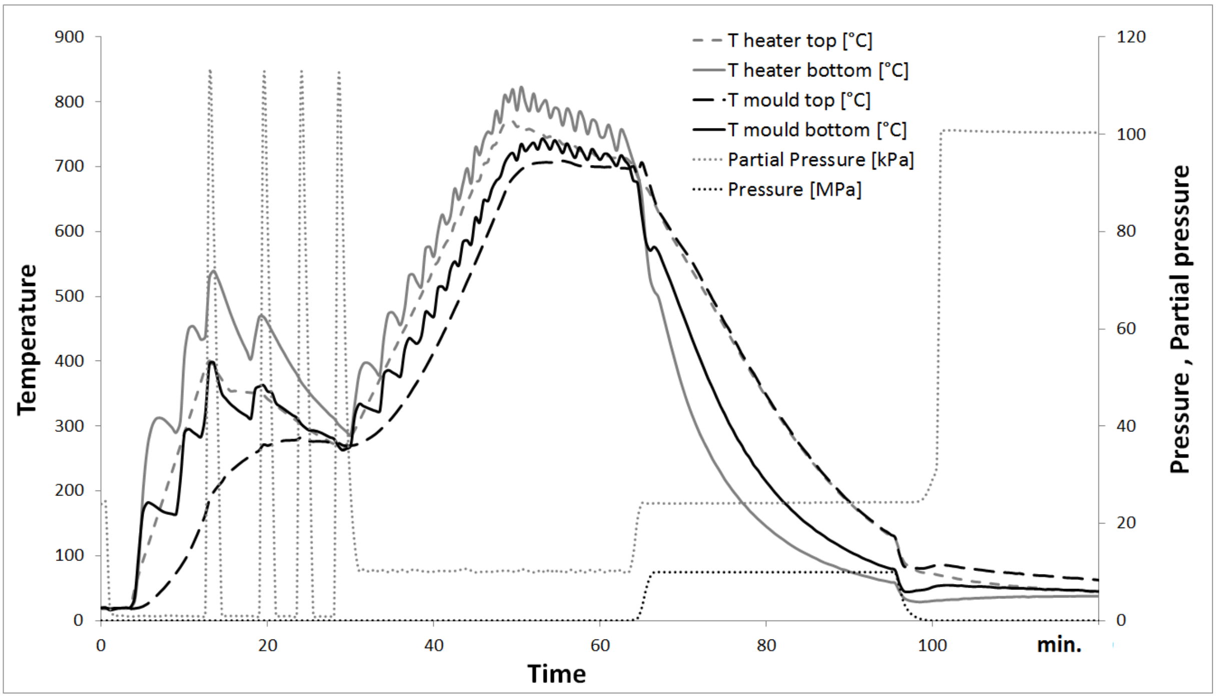


Figure 8: Temperature-pressure-time graph of infiltration of fibre optic sensors in carbon fibre reinforced 226D aluminium alloy.

6. RESULTS

To investigate the influence of Al_2O_3 sol-gel coating and the possibility of residual stresses reduction by the application of carbon fibres the microscopic analysis of optical fibres infiltrated by GPI process has been done. The analysis of optical fibres infiltrated without the carbon fibre reinforcement reveals the micro-fracture of their structure (Fig. 9).

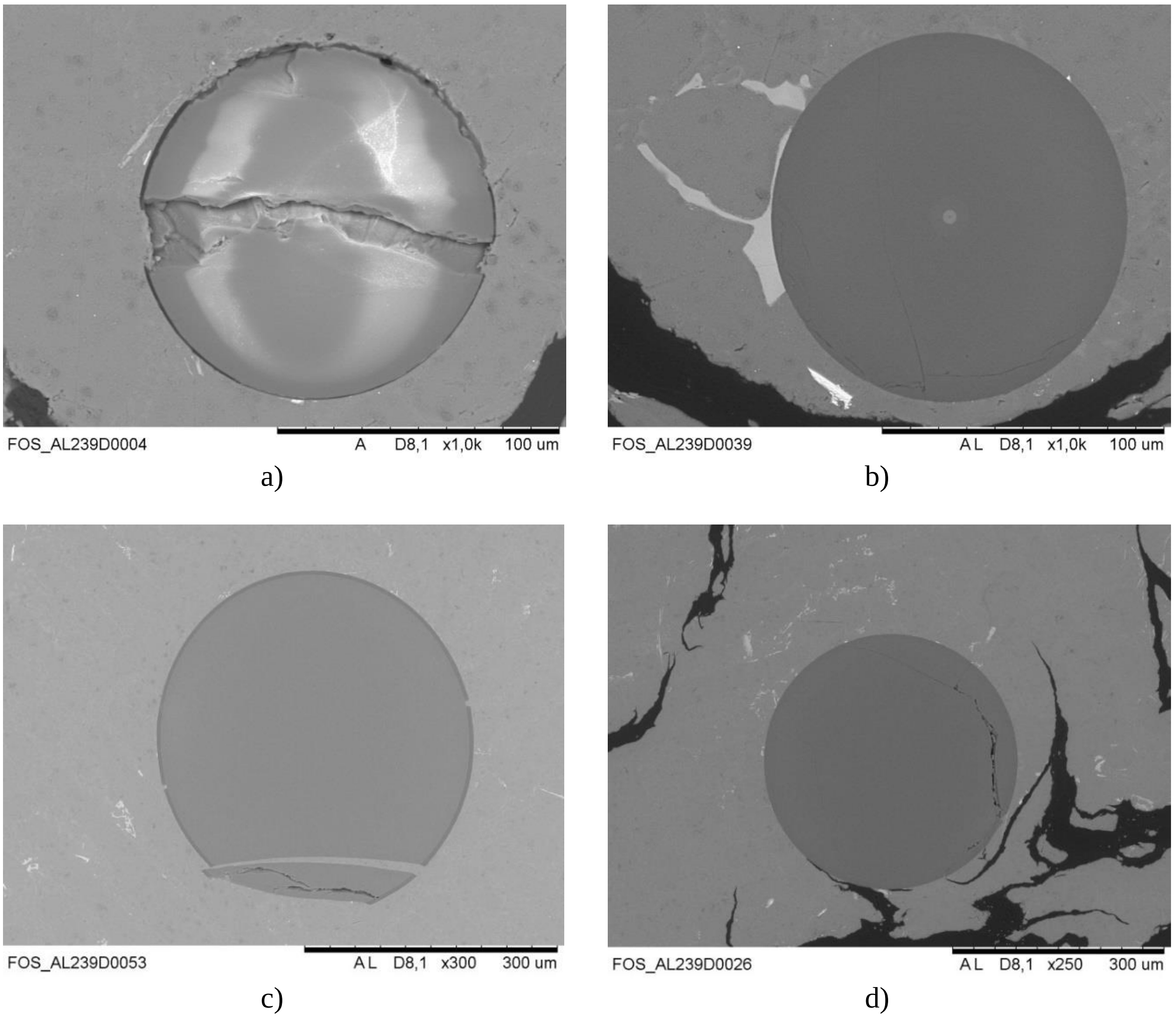


Figure 9: Microscopic analysis of optical fibres integrated in unreinforced 239D aluminium alloy: a) Silica Single-mode Optical Fibre ITU-T G.652.D without coating, b) Silica Single-mode Optical Fibre ITU-T G.652.D with Al_2O_3 sol-gel coating, c) Quartz UV 300/330 BN without coating, d) Quartz UV 300/330 BN with Al_2O_3 sol-gel coating.

It is visible that specimens without coating reveal more significant damage of their structure as well as lower adhesion to the aluminium alloy. This aspect is particularly noticeable in the Figure 4a with the crack along the boundary between optical fibre and matrix alloy. There are reasonable presumptions that this crack is caused as a relaxation phenomenon of extremely high thermal residual stresses formed during embedding process.

The optical fibres embedded in the vicinity of carbon fibre do not reveal any cracks due to lower mismatch of thermal expansion coefficients (Fig. 10).

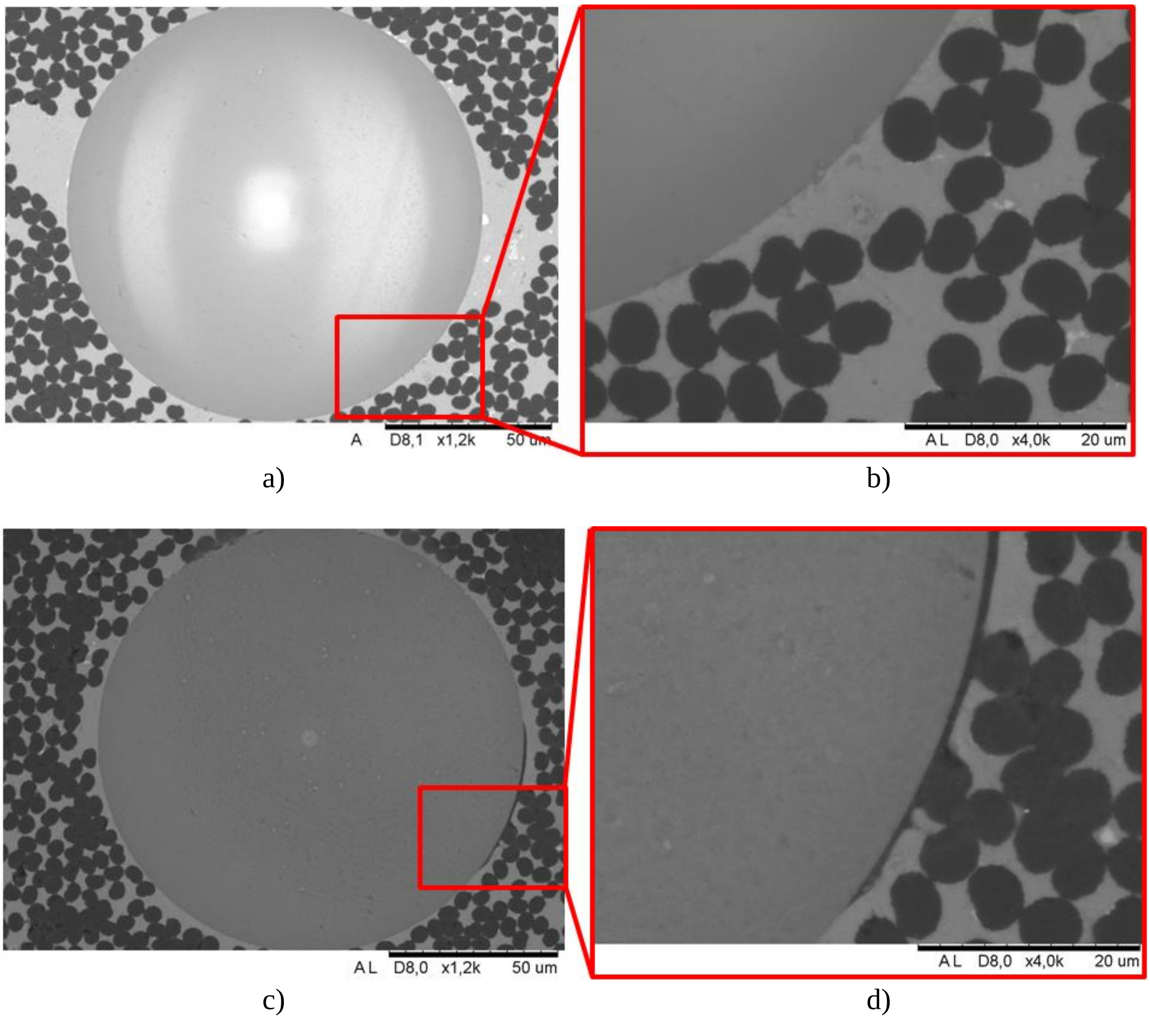


Figure 10: Microscopic analysis of optical fibres integrated in M40JB reinforced 239D aluminium alloy: a), b) Silica Single-mode Optical Fibre ITU-T G.652.D with Al_2O_3 sol-gel coating (1200x, 4000x), c), d) Silica Single-mode Optical Fibre ITU-T G.652.D without coating (1200x, 4000x)

This investigation also has shown that Al_2O_3 sol-gel coated specimens have better adhesion to the matrix alloy and reveal no additional cracks at the contact boundary with aluminium alloy.

To reveal the functionality of optical fibres after infiltration the test of transferring of the light through optical fibres has been done using different light colours and stereoscopic microscope (Fig. 11).

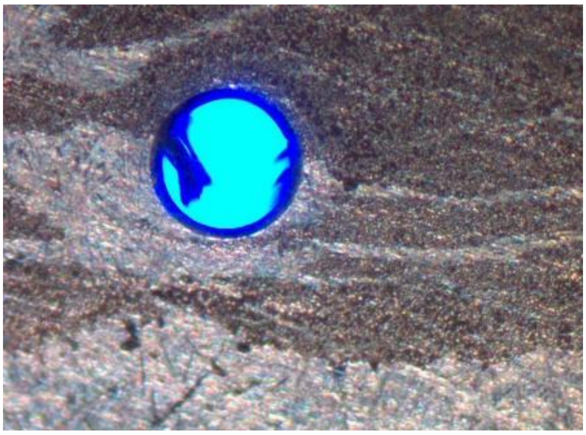


Figure 11: Test of the blue light transfer through Quartz UV 300/330 BN without coating using a stereoscopic microscope.

Although all optical fibres embedded in the carbon fibre reinforced aluminium composite have shown a successful light transfer, the specimens with sol-gel coating have been characterised by better adhesion to the matrix and no contact cracks. This fact allows the assumption that coated optical fibres may have less corrupted reflection of the stress state in the specimens and can be used as for integration into metal matrix composite for further monitoring purposes.

7. CONCUSSION AND OUTLOOK

Embedding of fibre-form sensors entails specific problems to be overcome inter alia by using protective and adhesive coatings. To receive successful integration of silica fibres the understanding of all phenomena occurring during high temperature casting processes is indispensable. Therefore, the in-depth thermal analysis by means of thermogravimetry and FEM analysis have been done a priori the infiltration process. Also adapting of the GPI method for successful embedding of optical fibres was performed.

Although, this was one of the first successful integration of optical fibres into metals and metal matrix composites, the prototyping of specimen with optical fibre ready for Structural Health Monitoring (SHM) requires further research on this field. One of the main obstacles hampering the usage of optical fibres as a sensor is related to the connection to signal interpretation unit. For this purpose the optical fibre needs to have at least 100 mm of its length protruded beyond the specimen. This problem can be overcome only with a sufficient protection of optical fibre in the transient between following areas: MMC plate – ingot – gas chamber.

The further research will be focused on the elaborating of an appropriate connection of the plate with embedded optical fibre to signal interpretation unit. The application of ceramic micro-pipes in the non-reinforced area can protect the fibre optic sensor form tremendous shrinkage and mismatch of thermal expansion coefficients causing detrimental residual stresses. Unfortunately incorporation of ceramic pipe into gas pressure infiltration process can frequently contributes to the capillarity effect what hampers the maintaining of the vacuum in the reinforced area of the plate as well as cause injection of pressurisation gas into structure of the specimen. This in consequence affects negatively the infiltration quality and causes formation of non-infiltrated areas.

The suitability assessment of GPI process to manufacture multifunctional metal matrix composites allows determining the next steps of further research. There are reasonable presumptions that an adopted GPI process will enable manufacturing of composites reinforced by sophisticated textile structures with integrated sensors.

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