EMBEDDING STUDIES FOR OPTICAL FIBRES IN METAL MATRIX COMPOSITES

Piotr MALCZYK[a], Maik GUDE[a], Bartlomiej PRZYBYSZEWSKI[a], Werner HUFENBACH[a], Andrzej CZULAK[a], Jerzy KALETA[b], Justyna KRZAK[b]

[a] *Institute for Lightweight Structures and Polymer Technology, Technical University of Dresden, Dresden, Germany, EU, piotr.malczyk@tu-dresden.de*
[b] *Wroclaw University of Technology, DMMS, Wroclaw, Poland, EU*

Abstract

Real-time monitoring of lightweight composite components by embedding additional sensors in the structure of composites becomes more and more popular in nowadays aerospace and automotive industry. However, polymer composites due to their low thermal stability are incapable of working at higher temperatures. Therefore the development of multifunctional Metal Matrix Composites (MMC) with embedded fibre optic sensors for real-time health monitoring is indispensable.

In this paper the pre-selection of optical fibres that can be suitable for embedding as optical fibres has been done. The preliminary investigation at commonly used optical fibres has shown the compulsion to design new appropriate coating.

Embedding of optical fibre as an integral part of carbon fibre reinforced lightweight alloys based MMC has been done via advanced Gas Pressure Infiltration (GPI). The analysis of thermal behaviour for optimization of desizing process has been a priori to optimize adhesive coating. This paper concerns problems related to the embedding of optical fibres into metal matrix composites. The quality analysis of infiltrated optical fibres has been done by the help of computed tomography and microscopic analysis. It has been shown that for further application of fibre optic sensors characterised by sufficient optical properties and adequate functionality the designation of favourable protective and adhesive coating is necessary.

Keywords: Metal matrix composites, optical fibres, lightweight alloys, sol-gel coating, gas pressure infiltration

1. INTRODUCTION

Rising demands for energy efficiency in the fields of mobility and mechanical engineering lead to increasing 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 in situ self-monitoring materials with integrated sensors and actuators are indispensable.

The development of smart materials is opening a new opportunities to construct a multifunctional composite structures with embedded sensors and actuators. This leads to additional non-structural functions without deterioration of mechanical properties and increasing of weight. Very good examples of 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 integration 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.

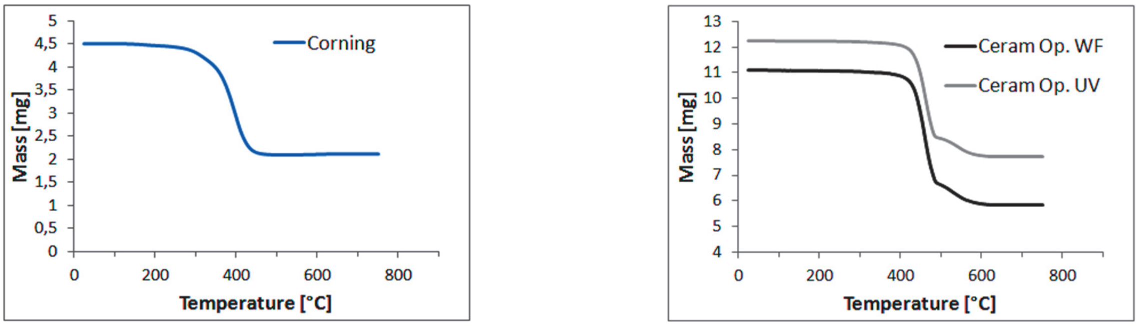
In a first step it is necessary to investigate the degradation behaviour of optical fibres in environments typical for the manufacture of metal matrix composites [4]. To manufacture first specimens with embedded optical fibres the GPI method has been used. For the reinforcement, 3D HTS as well as 2D HM carbon fibre textile has been selected. Specimens have been infiltrated by AZ91 magnesium and 226D aluminium alloys. The high temperature and high pressure are only few obstacles to overcome in the development of appropriate optical sensors. 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 infiltration process with quality analysis by means of scanning electron microscopy and computed tomography have been performed. The paper contains also preliminary investigation on appropriate coating of optical fibres.

2. THERMAL ANALYSIS OF SELECTED OPTICAL FIBRES

For embedding into metal matrix composites coatings of optical fibres have to be characterised by stability in temperature above the temperature of manufacturing process as well as the sufficient chemical resistance, or proper and predictable behaviour of coating in contact with alloy. Industrially manufactured polymer coatings as well as rare and expensive metal coatings can often be 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 from 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].

Within preliminary thermal analysis the thermogravimetry (TGA) of fibre has been done by **TGA/DSC1** analyzer from Mettler Toledo GmbH to estimate the temperature of desizing process of polymer coated optical fibres. 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® WF 300/330 BN, CeramOptec® UV 300/360 BN). Results are shown in the **Fig. 1**. The temperature range of TGA tests exceeds 720 °C which is the temperature of the infiltration process. The heating rate was 5 K/min.



a) b)

Fig. 1 TGA thermal analysis: Corning® (a); Ceram Optec WF and UV (b)

The optical fibres have lost their mass in a very explicit temperature range. Optical fibres do not exhibit any mass loss exceeding this temperature. Fused silica Corning® fibre has lost its mass in temperature range between 300 °C and 450 °C and quartz Ceram Optec® fibres in temperature range between 400 °C and 480 °C. Regarding to the fact that there is no mass lost above 700 °C there are reasonable presumptions that after performing an appropriate coating this optical fibres may be suitable for embedding in MMC by GPI process.

3. INFILTRATION OF OPTICAL FIBRES

The gas pressure infiltration process is characterised by the ability to manage a high temperature within maintaining pressure or vacuum. The whole process takes place in inert atmosphere, which allows using matrix alloys characterised by hazard of spontaneous combustion such as magnesium alloys. The schema Temperature-Time-Pressure-Cycle of GPI process is shown in **Fig. 2** [5, 10].

Infiltration process is divided in four steps:

- Optimized process of fibres in inert gas with chamber ventilation;
- melting of matrix alloy within vacuum maintaining;
- pressurisation of alloy at high temperature to infiltrate the reinforcement;
- chamber cooling process.

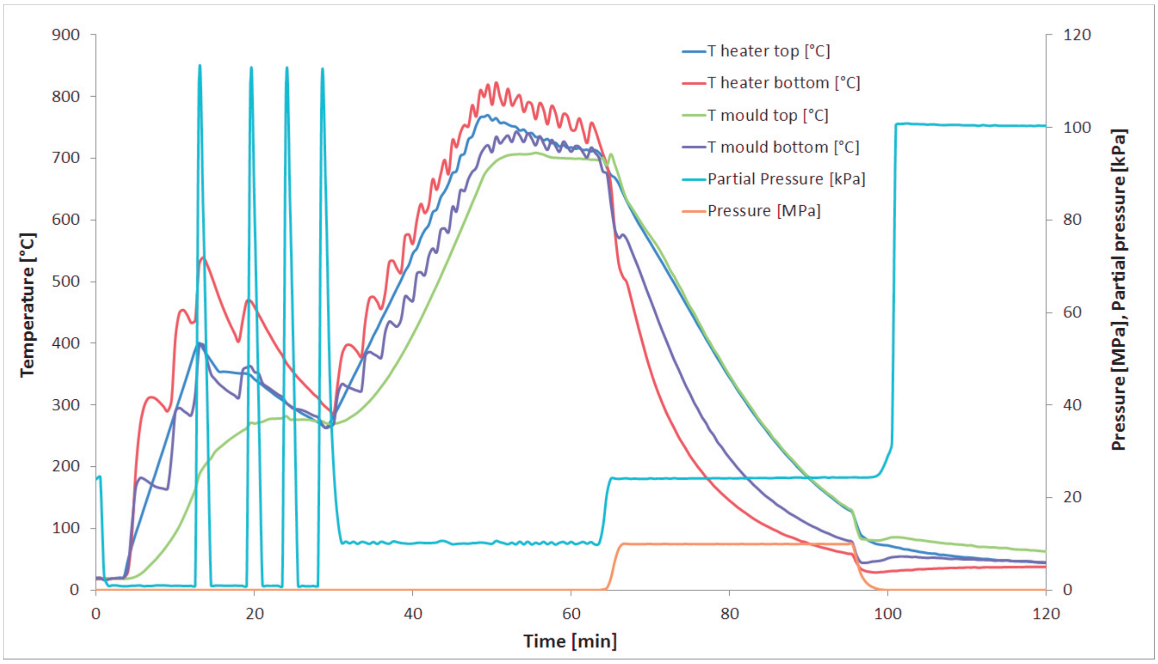


Fig. 2 Temperature-Time-Pressure-Cycle of GPI process [5]

4. QUALITY ASSESSMENT

To determine the quality of manufactured specimens computed tomography scans by the help of GE phoenix v|tome|x L450 computer tomography system and microscopic analysis by the help of SEM microscope HITACHI TM3000 have been performed. Computed tomography analysis has shown the destruction in whole length of optical fibres structure embedded in metal matrix composites (**Fig. 3**). This is an effect of contact of optical fibre with magnesium as well as mismatch of thermal expansion coefficient between them [4].

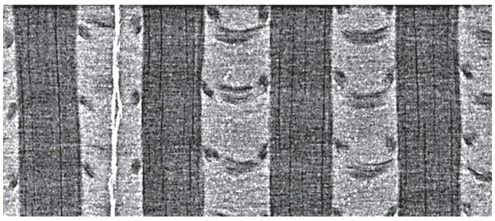


Fig. 3 Computed tomography scan of MMC with embedded optical fibres

Microscopic analysis has shown deterioration of the optical fibre structure with oxidation of cladding and core. It has been revealed that the main factor hampering the embedding of optical fibres is a destructive effect of magnesium diffusion into the structure of silica dioxide. **Fig. 4** shows probably eutectic of Mg/MgO which has taken oxygen from SiO_2 in the highly exothermal reaction $2\ Mg + SiO_2 = 2\ MgO + Si$. Therefore, free silicon elements have effused into alloy in the vicinity of optical fibre.

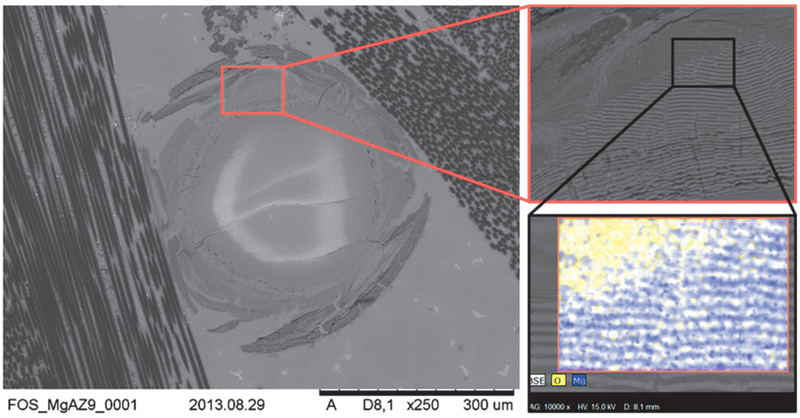


Fig. 4 Silica fibre optic sensors after infiltration in GPI process

Another hampering aspect that cannot be omitted is thermal stress by mismatch of thermal expansion coefficients between alloy and optical fibre. The shrinkage of infiltrating alloy on the surface of optical fibres contributes to longitudinal as well as transverse cracking (**Fig. 5**).

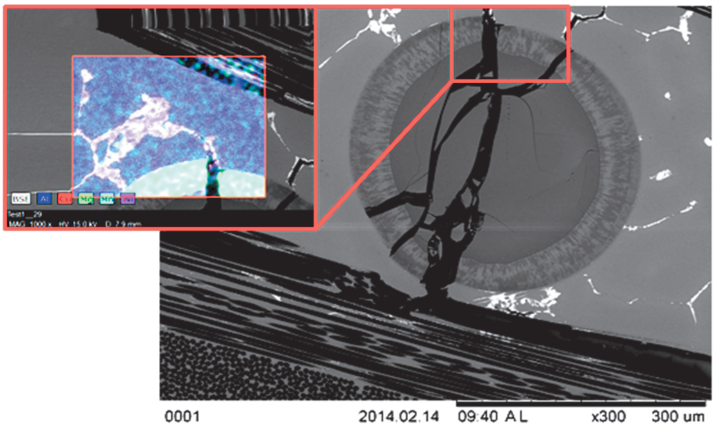


Fig. 5 Silica fibre optic sensors after infiltration in GPI process - longitudinal crack

The quality analysis revealed that it is indispensable to use specially adapted fibres for embedding in demanding manufacturing conditions of MMC. Therefore, effort to find appropriate coating, which enable to withstand the high temperatures within contact with melted alloy needs to be undertaken.

5. PRELIMINARY COATING

Application of additional coating on the optical fibres is vital to remain their optical properties and optimize their behaviour in demanding manufacturing conditions. Therefore, it is necessary to investigate and develop a new, protective coating providing a favourable mechanical conditions and chemical stability to embedded sensors [6, 10].

The optical fibres with and without additional residuals of buffer have been prepared to recoating and to adapt for further application in MMCs manufacturing processes. Residuals of buffer in form of carbon have been maintained to provide additional barrier between optical fibre and matrix. Silica sol-gel has been applied as a coating increasing the wettability and thus the adhesion between fibre and matrix alloy [11].

For further assessment regarding the embedding the infiltration process has been conducted with the same parameters as the infiltration of uncoated fibre optic sensors. The fibre has been fixed between two layers of carbon fibre reinforcement and infiltrated by lightweight alloys (**Fig. 5** and **Fig. 7**).

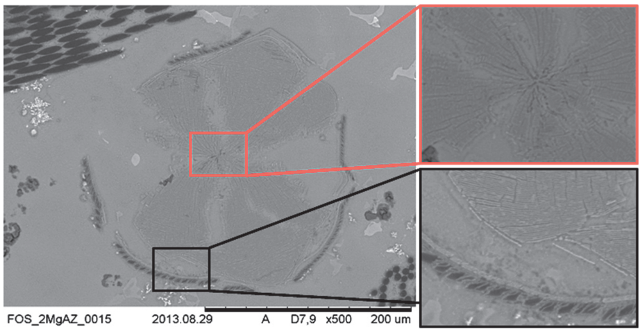


Fig. 6 Optical fibre without buffer embedded in magnesium alloy based composite - visible destruction of fibre structure and coating

Microscopic analysis of sol-gel coated fibres without buffer shows that due to discontinuity of coating layer the structure of optical fibre have been destroyed by the diffusion of magnesium alloy into the fibre.

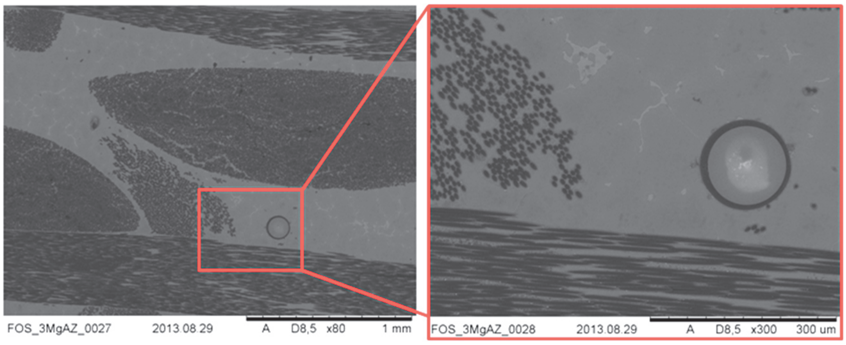


Fig. 7 Optical fibre with additional buffer embedded in magnesium alloy based composites - undamaged structure of fibre and coating

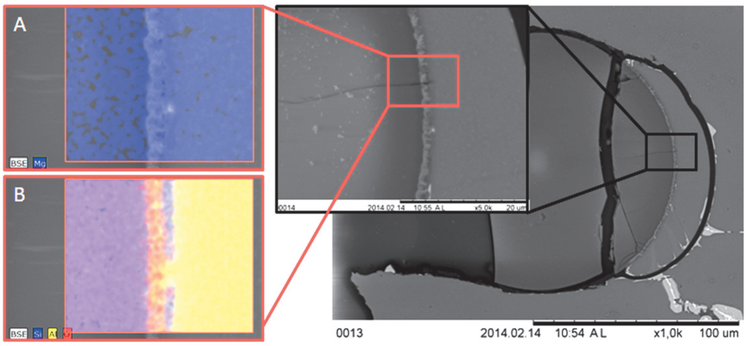


Fig. 8 Optical fibre with additional buffer embedded in magnesium alloy based composites - undamaged structure of fibre and coating

Fused silica fibre with buffer residuals and sol-gel coating provides continuous barrier and fibre has not been dissolved in the magnesium matrix alloy. The quality of the infiltration and adhesion between the fibre and matrix is sufficient and the structure of cladding and core is undisturbed.

The infiltration of sol-gel coated optical fibres in 226D aluminium alloy shows the phenomenon of formation of new multi-layer protective coating that can be suitable as a chemical barrier for magnesium alloy. The formed coating consists of the silicon and oxygen from sol-gel and aluminum elements diffused from alloy. There are reasonable presumptions that aluminum having high affinity to silica has formed with SiO_2 double layer coating

- Al_2O_3 and Al-Si. Moreover, microscopic analysis has shown the inhibition of magnesium elements by multilayered Al-Si-O coating (**Fig. 8**).

SUMMARY AND CONCLUSIONS

Common industrially used optical fibres as sensors are insufficient for embedding in metal matrix composites. Metal forming, casting and other processes adapted to receive high-tech composites based on alloys and continuous fibres are characterised by high pressures and high temperatures. Moreover, the contact of optical fibre with melted alloy can fully deteriorate its functionality due to chemical affinity of alloys to the elements from the structure of optical fibre within diffusion phenomenon. These hampering aspects need to be overcome by selecting or developing of new optical fibres with additional appropriate coatings.

Investigation of thermal behaviour of the optical fibres revealed that not only manufacturing conditions but also every process a priori has tremendous influence on the structure and health of fibre in final product. Therefore to maintain their optical functionality and in consequence develop fully applicable optical fibres ready to work with metal matrix composites the determination of thermal behaviour, desizing process, suitable infiltration condition and favourable coating was done.

It has been revealed that receiving of an advantageous infiltration quality and sufficient adhesion of optical fibres with matrix alloy requires the development of specific coatings. Highly adhesive barrier protecting optical fibres from aggressive impact of alloys is necessary to avoid the diffusion phenomena of magnesium elements into the structure of fibre, what in consequence cause the deterioration of its optical properties.

This paper contributes to pre-selection of most promising optical fibres capable of withstanding complex manufacturing conditions of MMCs. There are reasonable presumptions that quartz and fused silica optical fibre types could work properly within the infiltration process. However, for determination of most appropriate fibre it is vital to undertake the analysis of wider spectrum of optical fibres and the development of coating within continuous optimization of manufacturing process.

REFERENCES

[1] GIBSON, R.F. A review of recent research on mechanics of multifunctional composite materials and structures. *Composite Structures*, 2010, Vol. 92, No. 12, pp. 2793-2810.

[2] PANOPOULOU, A., LOUTAS, T., ROULIAS, D., FRANSEN, S., KOSTOPOULOS, V. Dynamic fiber Bragg gratings based health monitoring system of composite aerospace structures. *Acta Astronautica*, 2011, Vol. 69, No. 7-8, pp. 445-457.

[3] CHANG, J., DOMMER, M., CHANG C., LIN, L. Piezoelectric nanofibers for energy scavenging applications. *Nano Energy,* 2012, Vol. 1, No. 3, pp. 356-371.

[4] HUFENBACH, W., GUDE, M., CZULAK, A., MALCZYK, P., GESKE, V. In-situ analysis of damage mechanisms of carbon fibres aluminium metal matrix composites (3D-CF/Al-MMC) with the help of computer tomography. In *E-MRS 2012*.

[5] HUFENBACH, W., GUDE, M., CZULAK, A., GRUHL, A., MALCZYK, P., ENGELMANN, F. Carbon fibre light metal composites manufactured with gas pressure infiltration methods. *Production Engineering Innovations & Technologies of the Future*, Wroclaw, 2011, pp. 91-105.

[6] HUFENBACH, W., GUDE, M., CZULAK, A., MALCZYK, P., WINKLER, A. Thermal analysis of 3D-CF/Al-MMC by means of DSC and dilatometry tests. *Composites Theory and Practice*, 2013, Vol. 13, No. 2, pp. 96-101.

[7] BOQUAN JIANG et al. Optimization and kinetics of electro-less Ni-P-B plating of quartz optical fibre. *Optical Materials,* 2009, Vol. 31, pp. 1532-1539.

[8] SCHMID, S.R., TOUSSAINT, A.F. *Optical fiber coatings*. Specialty Optical Fibers Handbook, 2006, Chapter 4.

[9] BOTTOM, R. *Thermogravimetric analysis. Principles and applications of thermal analysis*. Editor Paul Gabbott, Blackwell Publishing, 2008.

[10] HUFENBACH, W., ULLRICH, H., GUDE, M., CZULAK, A., MALCZYK, P., GESKE, V. Manufacture studies and impact behaviour of light metal matrix composites reinforced by steel wires. *Archives of Civil and Mechanical Engineering*, 2012, Vol. 12, No. 3, pp. 265-272.

[11] TKACZYK, M., KRZAK-ROS, J., KALETA, J. Evaluation of mechanical and physicochemical properties of protection coatings obtained by the sol-gel method. *Materials Science*, 2012, Vol. 48, Issue 3, pp. 323-331.