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INFLUENCE OF DIFFERENT ALUMINIUM ALLOYS ON THE MATERIAL PROPERTIES OF CF/Al-MMC MANUFACTURED BY GPI METHOD

Carbon fibre (CF) reinforced aluminium (Al) composites show a high potential for lightweight design of structural components subjected to thermo-mechanical loadings. The relatively high stiffness and strength of the metal matrix allow the introduction of extremely high forces, thereby enabling a much better exploitation of the existing lightweight construction potential of this material in comparison to other composite materials. The manufacture of CF/Al-composites by the help of an advanced differential gas pressure infiltration (GPI) technique was developed at ILK, TU Dresden. Specimens made of carbon fibre reinforced aluminium metal matrix composites (CF/Al-MMC) were manufactured by GPI technology using moulds of graphite, nickel coated carbon fibres and different types of aluminium matrices. Examinations such as tensile tests, microscopic analysis and inspections of fracture surfaces provide a relation between mechanical properties of the manufactured CF/Al-MMC and the formation of their microstructure during the gas pressure infiltration process subjected to the type of aluminium matrix.

Keywords: **composites, carbon fibre-reinforced aluminium, gas pressure infiltration, MMC**

WPŁYW RÓŻNYCH STOPÓW ALUMINIUM NA WŁASNOŚCI MATERIAŁOWE CF/Al-MMC WYKONANYCH ZA POMOCĄ METODY GPI

Kompozyty wykonane z aluminium (Al) wzmocnionego włóknem węglowym (CF) wykazują ogromny potencjał w konstrukcjach lekkich elementów poddanych termomechanicznym obciążeniom. Stosunkowo duża sztywność i wytrzymałość osnowy metalowej umożliwia przeniesienie niezwykle dużych obciążeń, co pozwola na znacznie lepsze wykorzystanie istniejących możliwości konstrukcyjnych tego materiału w porównaniu do innych materiałów kompozytowych. Produkcja kompozytów CF/Al- za pomocą zaadaptowanej infiltracji ciśnieniowej (GPI) została opracowana w ILK, TU Dresden. Próbki aluminium wzmocnionego włóknem węglowym (CF/Al-MMC) zostały wykonane technologią GPI z użyciem form grafitowych z wykorzystaniem włókien węglowych powlekanych niklem oraz różnych rodzajów osnów aluminiowych. Przeprowadzone badania wytrzymałości na rozciąganie oraz analiza mikroskopowa powierzchni pękania pozwoliły dostarczyć informacji o zależnościach pomiędzy właściwościami mechanicznymi wytwarzanych CF/Al-MMC oraz powstałą mikrostrukturą w czasie procesu infiltracji gazowej w odniesieniu do rodzaju zastosowanej osnowy aluminiowej.

Słowa kluczowe: **kompozyty, kompozyty aluminiowe wzmacniane włóknem węglowym, infiltracja gazowa, MMC**

INTRODUCTION

Constantly rising demands on extremely stressed lightweight structures, particularly in traffic engineering as well as in machine building and plant engineering, increasingly require the use of endless fibre-reinforced composite materials which, due to their selectively adaptable characteristics profiles, are clearly superior to conventional monolithic materials.

Carbon fibre reinforcements embedded in the light metal matrix offers improved properties of these metal matrix composites (MMC), thus causing better creep resistance, especially at high operating temperatures, and good energy absorption behaviour, as well as increased stiffness and strength particular under superposed thermal loading conditions. Such reinforced metal-matrix composites offer extraordinary lightweight construction properties, even at higher permanent operating temperatures, and thus are clearly superior to classic fibre or textile-reinforced synthetic composites.

However, a broad, seminal utilisation of this young group of CF/Al-MMC for lightweight structures is currently strongly inhibited by materials scientific obstacles, as well as a lack of calculation methods, design principles and processes suitable for serial production.

In the development of composite components made from CF/Al-MMC it is important to match the metal matrix alloy and the fibre as well as the textile reinforcement and the component structure to one another in optimal fashion, which inevitably leads to close interlocking of processes relevant to material and structure [1-13]. Hence, investigations to the applicability of different aluminium matrix alloys should make a contribution to this task.

EXPERIMENTAL

Materials

For investigation two die casting alloys AlSi9Cu3 (Fe)* and AlSi9Mn as well as pure aluminium Al 99.99 (Tab. 1) were used to manufacture planar specimens with carbon fibre reinforcement via gas pressure infiltration (GPI) technique.

The secondary casting alloy AlSi9Cu3 (Fe) is the much used universal alloy in die casting, marked by less affinity to shrinkage and internal shrinkage cavities. The alloy was prepared and modified with 1% of magnesium (Mg) and 0.03% of strontium (Sr) in the Silesian University of Technology in Poland. The selected alloy composition are assures good technological properties especially castability and viscosity, moreover they improvement of the carbon fibres' surface wettability [14-17]. The primary casting alloy AlSi9Mn was prepared by Trimet Aluminium GmbH and is marked by a high ductility due to additions of manganese (Mn) and molybdenum (Mo) instead of iron (Fe). Furthermore the alloy was also modified with Sr for refinement [18].

For unidirectional (UD) reinforcement in loading direction, high tenacity (HT) carbon fibres by Toho Tenax (HTS 40 12K A23 MC) were applied. The fibres are marked by an electrochemical nickel (Ni) coating with a thickness of about 0.25 µm. As shown in literature [19-28] the use of fibres with Ni-coating significantly improves the wetting of carbon fibres.

Gas pressure infiltration

The manufacture of UD-reinforced specimens was made by GPI-technique. With the aid of special adapted graphite moulds planar samples (150 × 65 × 2 mm^3) could be manufactured with a nominal fibre volume fraction of V_f = 20%.

The procedural principle of the GPI-process is generally characterised in four steps (Fig. 1). In the first process step (1), the fibre preform, the mould and the Al-alloy are heated up to the temperature exceeding the liquidus temperature of Al-alloy in vacuum condition (2). After exceeding the liquidus temperature and initial infiltrating of the preform, a high argon gas pressure is applied to improve the infiltration by minimisation of the porosity (3). The last step consists in relatively fast cooling of the autoclave chamber by ventilation with cooled protective gas (e.g. argon).

Mechanical testing and microstructural characterisation

The reinforced GPI-samples were processed to planar tensile specimens (110 x 15 x 2 mm^3) with glass fibre reinforced plastic loading (GFRP) supports in accordance with DIN EN ISO 527-5. The determination of the mechanical material properties were made on a Zwick 1475

TABLE 1. **Nominal composition of pure aluminium and aluminium alloys (wt. %, balance: Al)**
TABELA 1. **Zestawienie składu czystego Al oraz stopów Al (% wag., reszta Al)**

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ni	Ti	Sr
AlSi9Cu3 (Fe)*	9.45	0.842	2.29	0.335	1.04	0.796	0.0749	0.0896	0.0231
AlSi9Mn	8.88	0.069	0.143	0.506	0.0442	0.0123	0.0087	0.0315	0.0213
Al99.99	0.0078	< 0.0010	0.0011	< 0.0010	0.0009	< 0.0050	0.0083	0.0017	0.0001

* modified alloy: AlSi9Cu3 (Fe) with 1% Mg and 0.03% Sr

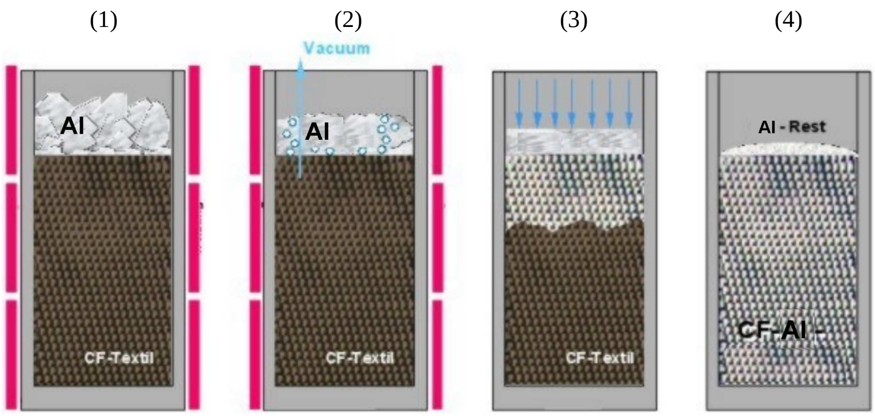

Fig. 1. Procedural principle of the gas pressure infiltration (GPI) technique
Rys. 1. Kroki podstawowe infiltracji gazowej

tensile testing machine with a test speed of 0.5 mm/min. The strain was measured by a clip-on extensometer.

Subsequently, the fracture surfaces of tensile specimens were inspected with a scanning electron microscope (SEM) of type Zeiss DSM 982 Gemini, while the investigation of the microstructure after the GPI-process, based on metallographic samples, was particularly carried out using a light microscope of the type Zeiss Axiotech Vario.

RESULTS AND DISCUSSION

Mechanical properties

After tensile tests, all specimens are marked by a fracture surface transverse to the load direction (normal fracture) (Fig. 2) and the tensile strength and the elongation seem to be at the same level, independent of type of Al-matrix. In contrast, preliminary test with unreinforced specimens provided values of elongation in the range of 0.5% (AlSi9Cu3 (Fe)*), 4.3% (AlSi9Mn) and > 20% (Al99.99). However, the elongation of reinforced specimens are significant lower than those of the fibres HTS 40 12K A23 MC with about 1.2% [34].

Fig. 2. Broken CF/Al-MMC specimen after tensile test

Rys. 2. Próbka CF/Al-MMC po badaniu

TABLE 2. **Determined values of tensile strength and elongation**

TABELA 2. **Wyznaczone wartości wytrzymałości na rozciąganie oraz wydłużenia**

	Al99.99	AlSi9Cu3(Fe)*	AlSi9Mn
R_m, MPa	151	157	153
A, %	0.4	0.3	0.4

Microstructural characterisation

After a successful infiltration, independent of the type of Al-matrix alloy, CF/Al-MMC specimens' exhibit complete infiltrated fibre bundles with a nominal fibre bundle porosity less than 1% (Fig. 3 a-c).

Furthermore, the microstructure of the Al-matrices differs in several phase formations which have been formed during the GPI-process depending on alloy composition. Especially by the use of AlSi9Cu3 (Fe)*, the formation of Fe, Mn, Mg, Cu and Si rich phases can be observed in Figure 4a in addition to the Al-Si-eutectic. These phases are known as intermetallics [32, 33] and offer high values of microhardness. Particular coarse Al_5FeSi-needles (1475 HV 0.01 [33]) were found by X-ray observations, which are formed during low cooling rates and result in an increase of embrittlement. These phases are marked as dark lines in Figure 4b.

a)

b)

c)

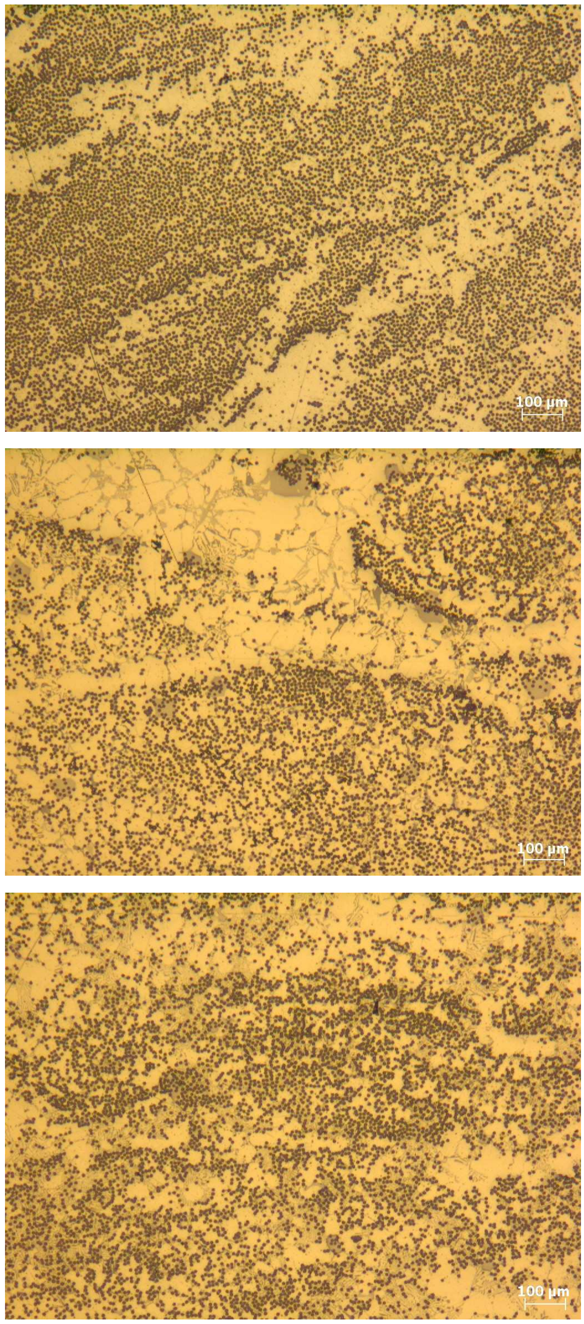

Fig. 3. Metallographic micrographs of CF/Al-MMC specimens, fibre orientation perpendicular to image plane: a) Al99.99, b) AlSi9Cu3 (Fe)*, c) AlSi9Mn matrix; magn. 50x

Rys. 3. Mikrostruktura próbek CF/Al-MMC, orientacja włókien prostopadła do przekroju, w zależności od zastosowanej osnowy: a) Al99.99, b) AlSi9Cu3 (Fe)*, c) AlSi9Mn; pow. 50x

Closer inspections of the fracture surface by SEM provide the evidence of a brittle fracture behaviour in the reason of high interface strengths, marked by missing fibre pull-outs (Fig. 5a-c). However, specimens with Al99.99 or AlSi9Mn matrix exhibit dimples of plasticity (Fig. 5 a,b), while specimens with AlSi9Cu3 (Fe)* matrix doesn't show any evidence of plasticity (Fig. 5c).

An explanation for this material behaviour is given by interfacial chemical reactions between the fibre coating or the fibre surface and the Al-alloy during the infiltration process. For instance, a distinctive dissolving of the Ni-coating occurs if Al-melt gets in contact with carbon fibres under formation of several phases [19-31]. By means of energy-dispersive X-ray (EDX) measurements clustered phases were detected close to the fibre filaments (marked in different brightness in Figure 6). They contain elements of Fe, Si and Cu from the Al-matrix and Ni basically from the fibre coating. Furthermore, the detected phases show cracks after the preparation of the metallographic specimens so that these phases can be considered to be hard and brittle like intermetallic compounds.

Another phase formation which can be expected at the interface between carbon fibre and Al-matrix is aluminium carbide (Al_4C_3). The formation of this phase

a) b)

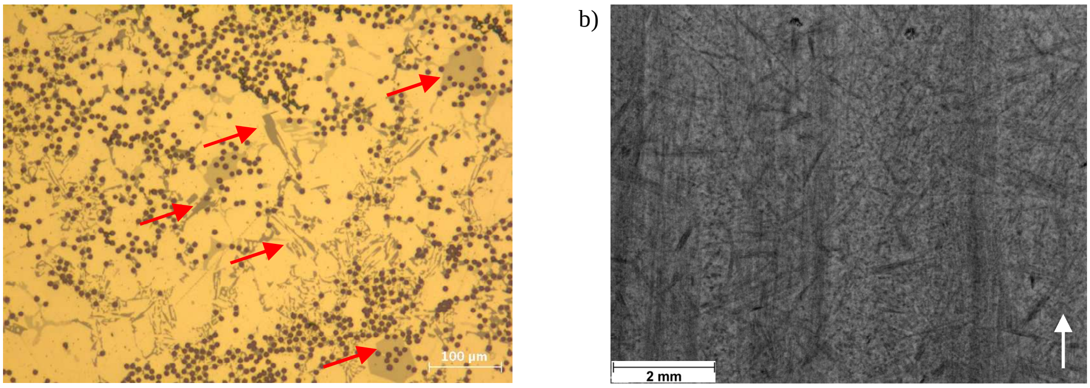

Fig. 4. a) Metallographic micrograph of CF/Al-MMC specimen with AlSi9Cu3 (Fe)* matrix (fibre orientation perpendicular to image plane), b) X-ray micrograph of CF/Al-MMC specimen (arrow show fibre orientation); magn. 100x

Rys. 4. a) Mikrostruktura CF/Al-MMC z osnową AlSi9Cu3 (Fe)* (włókna prostopadłe do przekroju), b) zdjęcie rentgenowskie CF/Al-MMC (strzałka pokazuje orientacje włókien); pow. 100x

a) b) c)

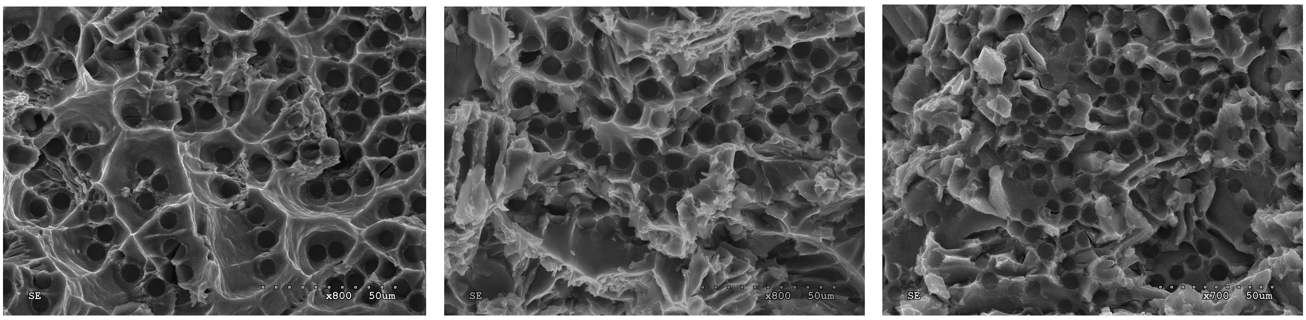

Fig. 5. SEM micrographs of fracture surfaces of CF/Al-MMC specimens with different Al-matrices: a) Al99.99, b) AlSi9Cu3 (Fe)*, c) AlSi9Mn

Rys. 5. Mikrostruktury powierzchni pęknięcia próbek CF/Al-MMC w zależności od zastosowanej osnowy: a) Al99.99, b) AlSi9Cu3 (Fe)*, c) AlSi9Mn

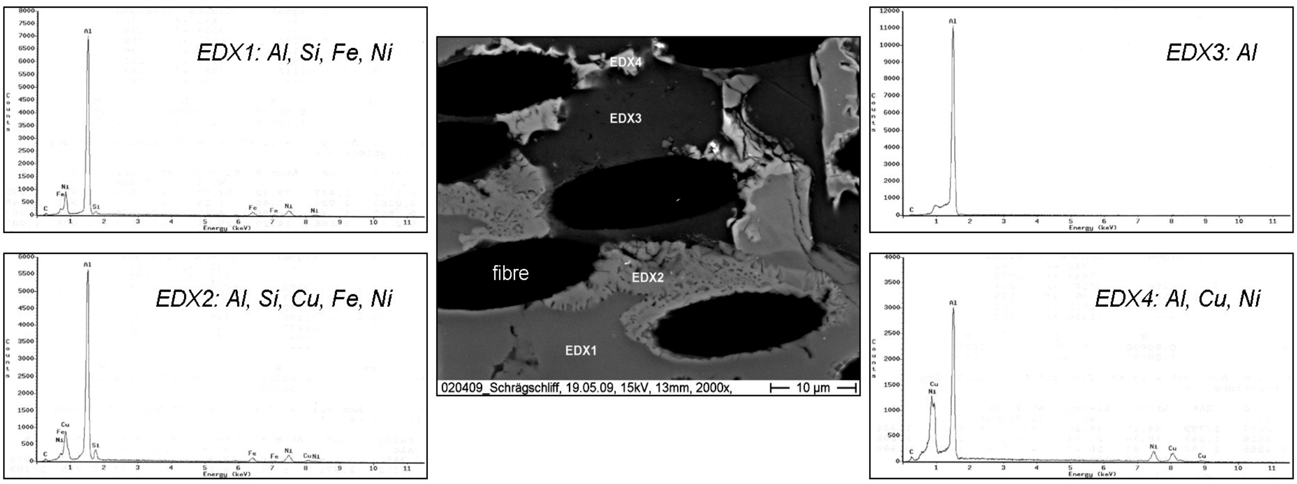

Fig. 6. SEM-micrograph and EDX-measurement inside a fibre bundle of a CF/Al-MMC specimen

Rys. 6. Mikrostruktura i analiza chemiczna wiązki włókien węglowych w próbce CF/Al-MMC

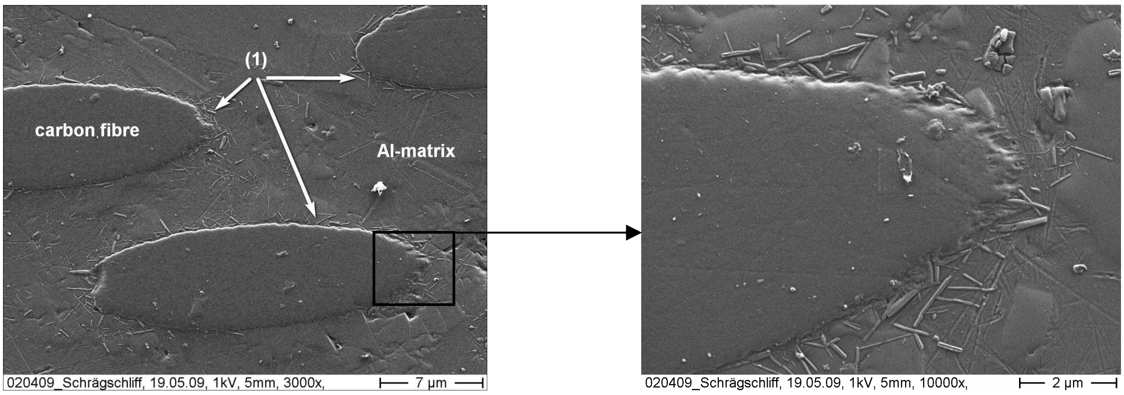

Fig. 7. Formation of needle-shaped phases (1) at the circumference of carbon fibres of CF/Al-MMC specimens with AlSi9Cu3 (Fe)* matrix alloy (fibre orientation perpendicular to image plane)

Rys. 7. Mikrostruktura wraz z powstałymi fazami w kształcie igieł (1) na powierzchni zewnętrznej włókien węglowych w osnowie AlSi9Cu3 (Fe)* (orientacja włókien prostopadła do przekroju)

leads to a strong decrease in the tensile strength of carbon fibres. Al_4C_3 can be characterised as a needle-shaped phase at the circumference of carbon fibres. SEM micrographs exhibit many needle-shaped phases at the circumference of the carbon fibres (Fig. 7). The form and size of these phases are equal to investigation results of [5], who certainly determined those as aluminium carbide.

CONCLUSION AND SUMMARY

The results are summarized as follows:

1. By means of special adapted GDI-technique a successful manufacture of UD reinforced planar CF/Al-MMCs was realised with complete infiltrated fibre bundles within a composite porosity less than 1%.
2. The tensile strengths and the elongations of UD reinforced CF/Al-MMC specimens with different types of Al-matrices seem to be limited at the same level, although large differences exist particular for the elongation of the plain Al-alloys.
3. The microstructure of CF/Al-MMC specimens with AlSi9Cu3 (Fe)* is characterised by the formation of several phases. Especially coarse, hard Al_5FeSi-needles were detected by X-ray examinations.
4. SEM observations provide the fact of a brittle fracture behaviour based on missing fibre pull-outs of broken fibre filaments. However, dimples of plasticity indicate a ductile fracture behaviour for matrices of Al99.99 and AlSi9Mn but not for AlSi9Cu3 (Fe)*.
5. Other phase formations due to the dissolving of the Ni-coating or the formation of aluminium carbide at the fibre surface contribute to a significant decrease in mechanical properties of CF/Al-MMCs.

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