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STUDY OF MANUFACTURE OF CF/Al-MMC WITH AID OF THE GAS PRESSURE INFILTRATION METHOD

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. Especially composites with textile reinforcement offer the highest flexibility for the adaptation of the reinforcing structure with regard to complex loading conditions. The load-adapted combination of three-dimensional reinforced semi-finished fibre products (textile preforms) made from carbon fibres (CF) with aluminium light metal alloys (Al) offers a considerable lightweight construction potential, which up to now has not been exploited. The textile CF 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. In addition, load-adapted CF/Al-MMC, due to 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.

These studies show that the gas pressure infiltration technique was successfully used to prepare composites consisting of unidirectional as well as bidirectional Ni-coated carbon fibres in different Al-alloy matrix systems and using of graphite moulds. Most of these investigations aim at the use of high tensile strength (HTS) fibres despite high reactivity with Al.

Keywords: **composites, carbon fibre-reinforced aluminium, infiltration**

PRÓBY WYTWARZANIA CF/Al-MMC ZA POMOCĄ METODY INFILTRACJI GAZOWEJ

Stale rosnące wymagania w stosunku do ekstremalnie obciążonych konstrukcji lekkich, szczególnie w zakresie inżynierii ruchu drogowego, a także w budowie maszyn i urządzeń, w coraz większym stopniu wymagają stosowania materiałów kompozytowych wzmocnionych włóknami ciągłymi, które z powodu ich dopasowanych właściwości posiadają wyraźnie większe możliwości od tradycyjnych monolitycznych materiałów. Zwłaszcza kompozyty włókniste oferują największe możliwości dostosowania struktury wzmocnienia do złożonych warunków obciążenia.

Odpowiednio dopasowane połączenie trójwymiarowo wzmocnionych półfabrykatów w postaci preform wykonanych z włókien węglowych (CF) z metalami lekkich stopów aluminium (Al) oferuje ogromny potencjał konstrukcji lekkich, który do tej pory nie został wykorzystany. Wzmocnienie węglowe w osnowie metali lekkich oferuje lepsze właściwości otrzymanych materiałów kompozytowych (MMC) z lepszą odpornością na pełzanie, szczególnie w wysokich temperaturach pracy, dobrą absorpcją energii, a także poprawę sztywności i wytrzymałości. Ponadto odpowiednio dostosowany do obciążenia CF/Al-MMC, ze względu na stosunkowo dużą sztywność i wytrzymałość osnowy metalowej, umożliwia przeniesienie dużych obciążeń, co pozwala na jeszcze lepsze wykorzystanie istniejącego potencjału tego materiału w porównaniu do innych materiałów kompozytowych.

Przedstawione badania pokazują, że metoda infiltracji gazowej (GPI) została z powodzeniem wykorzystywana do wytwarzania kompozytów metalowych wzmocnionych jedno- i dwukierunkowo włóknami z powłoką Ni z różnymi stopami Al z wykorzystaniem form grafitowych. W większości z tych badań użyto włókien o wysokiej wytrzymałości na rozciąganie (HTS) pomimo dużej reaktywności z Al.

Słowa kluczowe: **kompozyty, aluminium wzmacniane włóknami węglowymi, infiltracja gazowa**

INTRODUCTION

At present, aluminium alloy matrix composites are applied in automotive and machine sector and strategic sectors such as defence and aerospace, as well as in different segments of other engineering industries [1]. As a reinforcement material for aluminium matrix composites [2], high-modulus (HM) carbon fibres are considered in order to increase the strength and stiffness, to improve the electrical and thermal conductivities and to reduce the density. However, manufacture problems, such as poor wettability and damages of carbon-fibres have limited industrial application of these materials [3, 4]. Potential manufacturing methods for production of carbon-fibre reinforced aluminium-matrix composites are high-pressure die casting and squeeze casting for large-batch production as well as gas-pressure infiltration method for small-batch production and prototyping [5-7]. In particular, squeeze casting and die casting provide good infiltration quality of preforms [8]. These procedures consist of pushing or pressing the molten metal into preheated steel dies with carbon fibres using a piston and pressures in the range of 50÷150 MPa. Despite the good results obtained with these techniques, some difficulties remain related with air inclusions. Moreover, high pressure often leads to fibre damage or an inhomogeneous fibre distribution along the infiltration direction [9]. Consequently, a relatively low-cost production method for prototypes and test runs can be developed by using gas pressure to achieve infiltration. Different studies show that the gas pressure infiltration technique was successfully used to prepare composites consisting of Ni- and Cu-coated chopped carbon fibres as well as unidirectional Ni-coated carbon fibres and porous graphite preforms in different Al-alloy matrix systems [10-15]. Most of these investigations aim at the use of HM fibres due to their lower reactivity with Al compared to high-tensile-strength (HTS) fibres. However, HM fibres are inappropriate for textile reinforcement structures became their brittleness and stiffness are disadvantageous for textile processing.

The majority of other scientific activities has been performed especially in the context of particle--reinforced MMCs. Within these investigations, particularly emphasis was set however to friction and wear resistance as well as dry sliding and self lubrication of adapted composite materials for lightweight applications. Therefore different aluminium matrix alloys reinforced with ceramic particles such as SiC, Al_2O_3 or B_4C were used to improve the hardness, stiffness, strength and thermal resistance of the raw alloys [15-20]. Parallel to this topic, the activities of other researchers improve material properties e.g. tensile and compression strength, stiffness, vibration damping, fatigue resistance or coefficient of thermal expansion [20-25]. The investigators see advantages of discontinuously reinforced MMCs in easier fabrication routes, lower costs and nearly isotropic properties compared to endless-fibre-reinforced MMCs [22]. However the rate of increase in mechanical properties is strongly limited for particle reinforced MMCs; a higher potential is expected by endless-fibre-reinforced MMC on the basis of HTS carbon fibres as soon as technological obstacles are overcome.

GAS PRESSURE INFILTRATION EQUIPMENT, AUTOCLAV AND GRAPHITE MOULDS

The manufacture of CF/Al-MMC specimens is realised with the aid of gas pressure infiltration technique at the ILK. General advantage of the GPI technique in contrast to die casting and squeeze casting is the significantly lower processing pressure during the infiltration. The solidification takes place with a gas pressure, so that significantly fewer pores are created during the infiltration procedure. Additionally, in gas pressure infiltration the decisive process parameters, such as temperature, pressure and infiltration as well as cooling times can be adjusted selectively, allowing optimisation of the infiltration sequence. Moreover thin-walled infiltration moulds can be applied, which enable a better process control and reduced mould costs.

A laboratory GPI unit (Fig. 1), for a process pressure of 100 bar at temperatures up to 1200°C was initially used for the fabrication of CF-Al composites. The GPI unit offers a diameter of 150 mm and a height of 400 mm. The GPI unit is connected to computer system, which allows the online recording of process parameters in the heating zone and inside the graphite mould.

a)

b)

Fig. 1. Gas pressure infiltration unit at ILK (a) and graphite mould (b)

Rys. 1. Stanowisko (autoklaw) wykorzystywane do infiltracji gazowej (a) i forma grafitowa (b)

For the manufacture of specimens, precision moulds made of graphite were developed, which are characterized by following advantages:

- chemically inert and non-wettable regarding to the most metal melts
- high thermal resistance for cast applications
- high thermal cycle resistance regarding to long endurances
- high thermal conduction regarding to fast heating and cooling rates
- low thermal expansion coefficient to reduce thermal stresses.

The designed mould systems consist of an inner (Fig. 2) and an outer mould (Fig. 3) for the manufacture of planar specimens with a length of 150 mm, a width of 65 mm and a thickness of 0.5 to 2 mm.

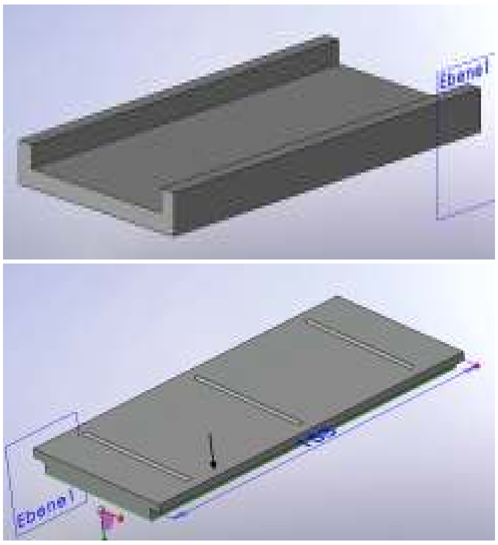


Fig. 2. Graphite inner mould for manufacture of plane specimens

Rys. 2. Model wewnętrznej formy grafitowej

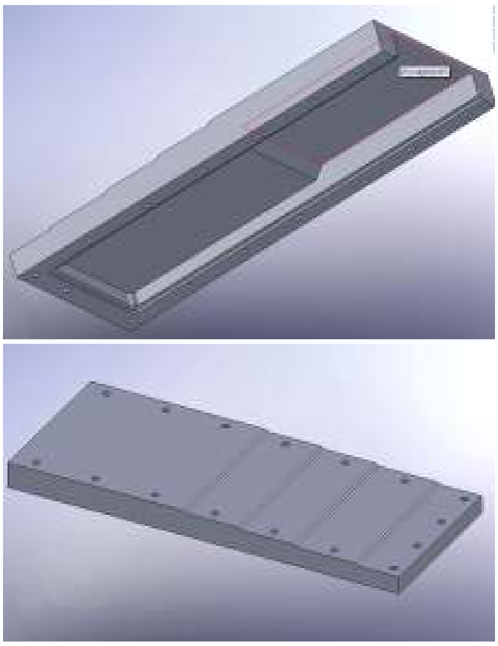


Fig. 3. Graphite outer mould for manufacture of plane specimens

Rys. 3. Model zewnętrznej formy grafitowej

COMPONENTS FOR GPI MANUFACTURE PROCESS

For the manufacture of CF/Al-MMCs, two types of CF reinforcements are selected. On the one hand, commercial fibres of the type HTS40 A23 12K MC by Toho Tenax, which exhibit an electrochemical Ni-coating with a thickness of 0.25 μm are used for the in-house manufacture of wound unidirectional (UD) preforms and bidirectional (BD) fabric preforms (Fig. 4).

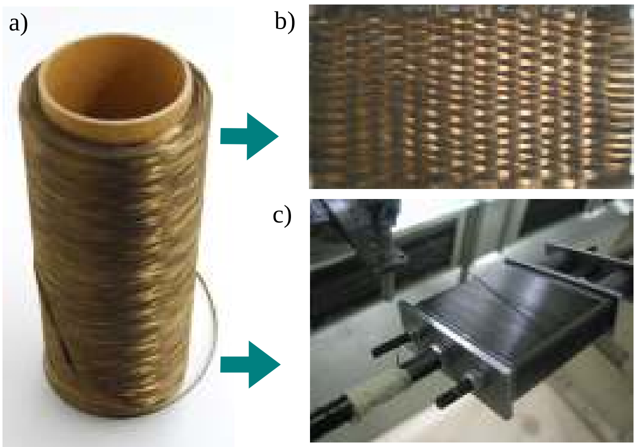


Fig. 4. Ni-coated fibres yarn (a), in-house manufactured woven BD-preform (HTS-BD) (b) and wound UD-preform (c)

Rys. 4. Włókna węglowe pokryte Ni (a), wykonana preforma BD (b) oraz nawinięta preforma UD (c)

On the other hand, commercial fibres HTA 40 E13 6K by Toho Tenax were used for infiltration studies on wound preforms and on fabrics. The fabrics are coated with Ni (P) by an electroless plating process (cooperation with Warsaw University of Technology). The coating is deposited as a result of the controlled reduction of metal salt in solution, which is catalyzed by the deposited metal (Fig. 5). Thereby, the bath composition with different reducing agents enables to vary the coating structure from amorphous to nanostructured. After deposition, the thickness of the coating amounts to max. 2.5 μm.

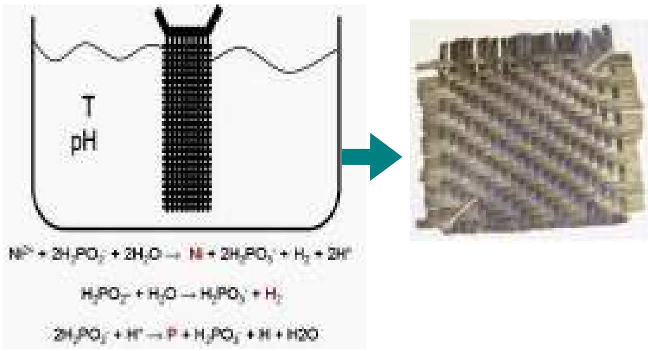


Fig. 5. Electroless Ni (P)-deposition of woven fabrics (HTA-BD) made by Politechnika Warszawska

Rys. 5. Pokrywanie Ni (P) preformy z włókien węglowych

In the frame of investigations, an unmodified AlSi9Cu3(Fe) aluminium alloy as well as modified AlSi9Cu3(Fe), aluminium alloys were used in the manufacture processes. The modified AlSi9Cu3(Fe) alloy, were prepared and modified together with Silesian University of Technology and for the modification of the selected alloy (226D), magnesium and strontium additions in the amount of 0.03% Sr and 1% Mg (226D_M) respectively were used.

First infiltration studies confirmed that aluminium alloys with a low liquidus temperature are predestined for manufacture of carbon reinforced aluminium matrix composites, because higher process temperature adversely affects the mechanical properties of carbon fibres.

GAS PRESSUER INFILTRATION PROCESS

The successful manufacture of CF/Al-MMC requires exact adaptations of the process preparation and the procedural principle. Dependent on the type of reinforcement, fibre coating and the type of the aluminium alloy, different steps of process preparation are necessary. The procedural principle of the GPI-process is generally characterised in four steps (Fig. 6).

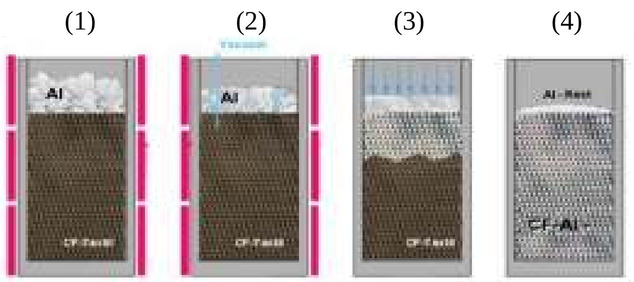


Fig. 6. Procedural principle of the gas pressure infiltration (GPI) technique

Rys. 6. Kroki podstawowe infiltracji gazowej

In the first process step (1), the fibre preform, the moulds and the Al-alloy are heated up to a temperature exceeding the liquidus temperature of the modified Al-alloy in vacuum condition (2). After exceeding the liquidus temperature and after initial preform infiltration, a high argon gas pressure is applied to minimise the porosity (3). In the last step, the GPI chamber is cooled down by ventilation with cooled protective gas (e.g. argon). The characteristics of the process, registered by the GPI-unit equipment, are shown in Figure 7.

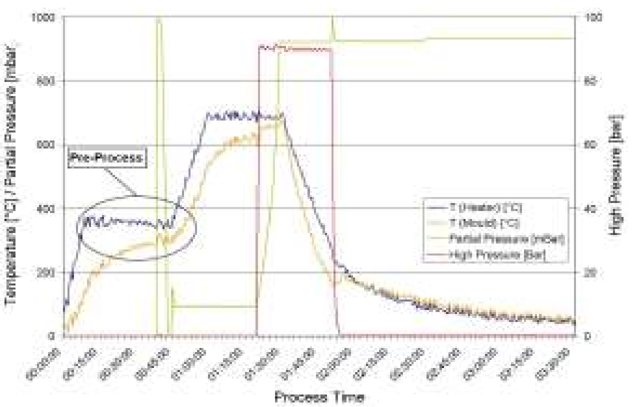


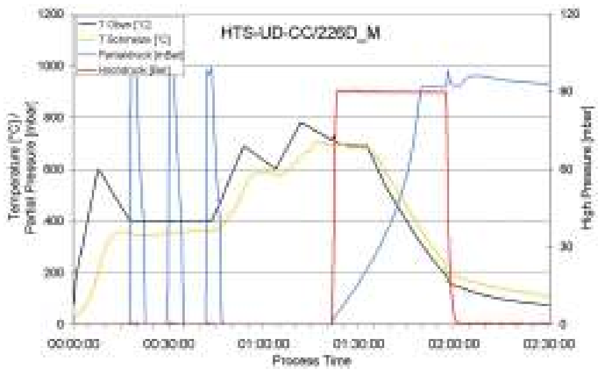
Fig. 7. Temperature-time-pressure-cycle of GPI process

Rys. 7. Wykres temperatury do czasu oraz ciśnienia - procesu GPI

The extraordinarily great bandwidth of variable reinforcement materials and aluminium matrices in the manufacture of carbon fibre reinforced aluminium by means of gas pressure infiltration methods requires a systematic approach for the selection of optimal parameters. In the course of these efforts, composite material properties were varied with respect to the parameters: heating temperature of outer and inner mould, casting temperature of the aluminium alloy and infiltration pressure.

The adaptation of the GPI-process parameters takes into consideration the results of thermal analyses of the used aluminium alloy. The infiltration of commercial Ni-coated fibres (HTS40 A23 12K MC) requires an additional isothermal fibre treatment ("Pre-Process" in Fig. 7) in order to remove the polymer standard sizing for an improved fibre wettability with aluminium melt. Typical temperature-time-pressure-cycles of the GPI process dependent on the different reinforcement materials are presented in Figure 8.

a)



b)

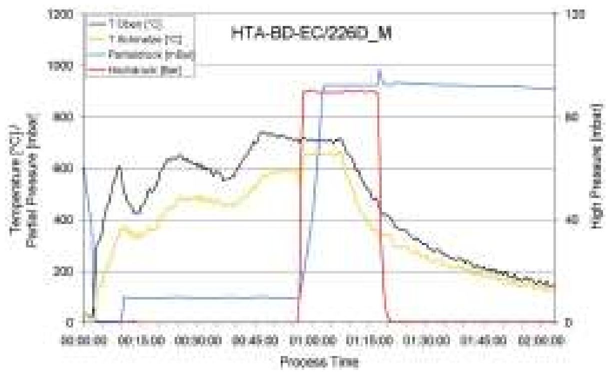


Fig. 8. Temperature-time-pressure-cycle of GPI process for different reinforcement materials

Rys. 8. Wykres temperatury do czasu oraz ciśnienia - proces GPI w zależności od materiału wzmocnienia

RESULTS

In the first phase the suitable adaptation of process parameters at the beginning of the infiltration process (isothermal fibre treatment) as well as melting time and temperatures for different aluminium alloys has been proven by good infiltration results (Fig. 9).

During multiple infiltration tests with the aid of the existing equipment at ILK, disadvantages of the used GPI-unit became obvious, which directly affect the mechanical properties of manufactured planar specimens:

- long duration of the process preparation
- long duration of the infiltration process

- combined heating of preform and alloy
- cooling of the MMC via the autoclave, thus low cooling rates
- limited control of the process,

and will be solved in the next phase of the research.

a)

b)

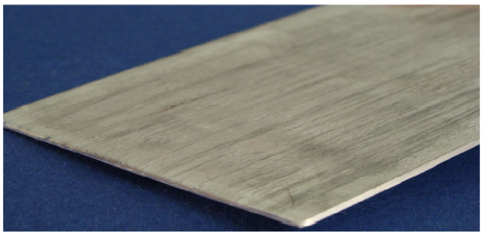


Fig. 9. Planar CF/Al-MMC specimens manufactured via GPI: a) HTS-BD-CC/226D_M; b) HTS-UD-CC/226D_M

Rys. 9. Próbki płaskie CF/Al-MMC wykonane w procesie GPI: a) HTS-BD-CC/226D_M; b) HTS-UD-CC/226D_M

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