KOMPOZYTY
COMPOSITES

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SIMULATION OF INFILTRATION PROCESS OF CARBON FIBRES BY ALUMINIUM ALLOY IN MODIFIED GPI METHOD

The constantly rising demands for lightweight structures, particularly in traffic engineering as well as in machine building and plant engineering, increasingly require the use of continuous fibre-reinforced composite materials. These materials, due to their selectively adaptable characteristic 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. This paper presents the procedure and evaluation of a gas pressure infiltration process (GPI) for the manufacture of carbon fibre-reinforced aluminium metal matrix composites (CF/Al-MMC). Furthermore, the development of a new furnace for a modified GPI method is presented. In order to verify the new design, numerical simulations of the heating in the furnace chambers were prepared, which finally formed the basis for the improvement of the furnace as well as the GPI process.

Keywords: carbon fibre-reinforced aluminium, pressure infiltration, metal matrix composites

SYMULACJA PROCESÓW INFILTRACJI WŁÓKIEN WĘGLOWYCH STOPEM ALUMINIUM W ZMODYFIKOWANEJ METODZIE GPI

Stale rosnące zapotrzebowanie na lekkie konstrukcje, szczególnie w zakresie inżynierii ruchu, a także w budowie maszyn i urządzeń oraz w przemyśle energetycznym, w coraz większym stopniu wymaga stosowania materiałów kompozytowych wzmocnionych włóknem ciągłym. Materiały te, dzięki możliwości selektywnego dopasowania charakterystyk materiałowych, wydają się być lepsze od zwykłych materiałów monolitycznych. Kompozyty wzmacniane materiałami z włókien oferują obecnie najlepszą elastyczność dostosowania struktury wzmocnienia do założonych warunków obciążenia. W niniejszym artykule przedstawiono przebieg oraz ocenę procesu infiltracji gazowej (GPI - ang. *Gas Pressure Infiltration*), zastosowanego do wytwarzania kompozytów aluminiowych z włóknami węglowymi (CF/Al-MMC). Ponadto zaprezentowano model autorskiego pieca do produkcji zmodyfikowaną metodą GPI. W celu weryfikacji nowej konstrukcji sporządzono numeryczne symulacje nagrzewania w poszczególnych komorach pieca, które w rezultacie pozwoliły na modyfikację pieca oraz procesu.

Słowa kluczowe: kompozyty metalowe, aluminium wzmacniane włóknem węglowym, infiltracja gazowa

INTRODUCTION

Considering innovative metal-matrix composite designs at an early stage is the key-factor for the realisation of economical lightweight systems for thermomechanical loading conditions. At present, aluminium (Al) metal matrix composites (MMC) are applied in the automotive and machine sector, 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 (CF) are considered in order to increase the strength and stiffness, to improve the electrical and thermal conductivities and to reduce the material density. Thereby, the use of HM-fibres is more suitable than high-tensile-strength (HTS) fibres due to their lower reactivity with Al. However, HM-fibres are inappropriate for textile processing within the manufacture of textile reinforcement structures. The main reason is their higher brittleness and stiffness compared to HTS-fibres. Furthermore, manufacturing problems such as poor wettability and damage of the carbon fibres lead to a limited industrial application of these materials [3, 4]. Potential manufacturing methods for the production of carbon fibre-reinforced aluminium metal matrix composites (CF/Al-MMC) are high-pressure die casting and squeeze casting for large-batch production as well as gas pressure infiltration (GPI) for small-batch production and prototyping [5-7]. In particular, squeeze casting and die casting provide good infiltration quality of the preforms [8]. These procedures consist in

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 to air inclusions. Moreover, high pressure often leads to fibre damage or inhomogeneous fibre distribution along the infiltration direction [9]. Consequently, a relatively low-cost production method for prototypes and test runs shall be developed by using gas pressure to achieve infiltration, which was already 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].

GAS PRESSURE INFILTRATION EQUIPMENT AND PROCESS

The manufacture of CF/Al-MMC specimens is realised with the aid of the gas pressure infiltration technique at the ILK. The general advantage of the GPI technique in contrast to die casting and squeeze casting is the significantly lower processing pressure during infiltration. Solidification takes place with a gas pressure so that significantly fewer pores arise during the infiltration procedure. Additionally, in gas pressure infiltration, the decisive process parameters such as temperature, pressure and infiltration duration 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 better process control and reduced mould costs.

A laboratory GPI unit (Fig. 1a), 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 350 mm. The GPI unit is connected to a computer system which allows an online recording of the process parameters in the heating zone and inside the graphite mould.

During multiple infiltration tests with the aid of the initial equipment at ILK, disadvantages of the used high temperature autoclave occurred, which directly affect the quality of the manufactured planar specimens:
- long time of process preparation,
- long time of infiltration process,
- combined preform and alloy heating,
- cooling of MMC via the autoclave, thus low cooling rates,
- limited control of the process.

For this reason, a new furnace for a modified gas pressure melt infiltration technique was developed. The designed high-pressure furnace consists of two separate chambers (melting chamber and injection chamber) to allow separated and fast heating of the Al-alloy and fibre preform in a protective gas atmosphere. For fast cooling-down of the manufactured specimen, the mould is retracted immediately from the injection chamber with the help of a sideway (Fig. 2).
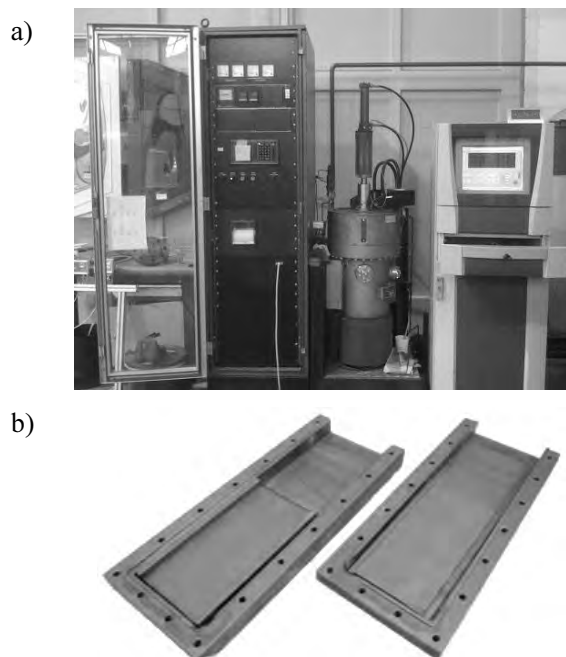

Fig. 1. Gas pressure infiltration unit at ILK (a) and graphite mould (b)
Rys. 1. Urządzenie wykorzystywane do infiltracji gazowej w ILK (a) i forma grafitowa (b)

Fig. 2. Two-chamber high-pressure GPI-oven for precise controlled infiltration process of 3D-CF/Al-MMC
Rys. 2. Zaprojektowany dwukomorowy piec przeznaczony do infiltracji gazowej 3D-CF/Al-MMC

The principle of operation for the two-chamber high-pressure GPI-furnace is presented in Figure 3. As a first step, the melt and injection chambers are vacuum vented (residual pressure of approximately 1 Pa). The Al-alloy is melted in the graphite crucible of the upper chamber by the heating elements. Simultaneously, in the injection chamber the preform is preheated and outgassed (Step 1). When the desired temperatures of the molten aluminium and of the fibre preform are reached, the power for the preform preheating is switched off and the graphite finger is opened to enable the molten metal to flow from the upper to the lower chamber (Step 2). Then, the graphite finger is closed and the protective gas is rapidly injected until the desired pressure is achieved, in order to press the metal into the preform (Step 3). Immediately thereafter, the pressure of the protective gas is lowered and the casting is cooled down by an air stream. After solidification, the mould with the manufactured specimens is immediately removed from the injection chamber (Step 4).
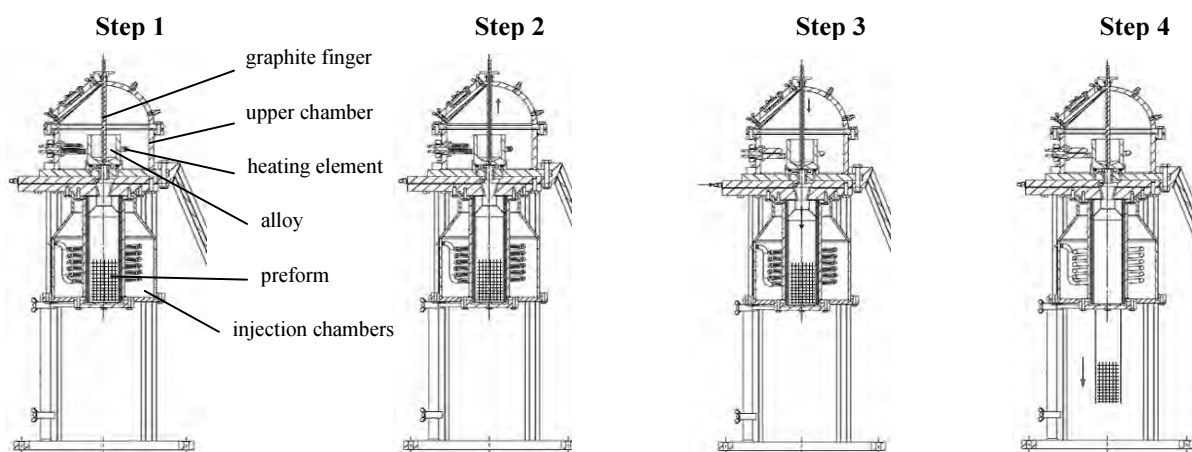
Fig. 3. Processing steps of two-chamber high-pressure GPI-oven

Rys. 3. Etapy przebiegu procesu infiltracji gazowej w zaprojektowanym piecu

The main advantages of the developed oven for the modified GPI process are:
- compact design,
- separated and fast heating of alloy and perform,
- melting of aluminium in protective gas atmosphere,
- fast cooling of specimens,
- possible use of different moulds,
- short manufacture and setting-up times,

from which significant improvements in the material properties can be expected.

For the purpose of verifying the new furnace design, it was necessary to obtain information about the time in which both chambers can be heated up to the required temperatures. The analysis was connected with the problem of heat transfer by radiation in vacuum conditions, which was investigated using the finite element method by utilizing the Flow Modeling Software *FLUENT* of the *ANSYS Company*.

Materials

The investigated CF/Al-MMC consisted of a matrix from the modified aluminium alloy No. 226D (AlSi9Cu3(Fe)) and carbon fibres as a reinforcement.

The furnace components were made from DIN 1.4301 steel while the material for the radiant heaters was defined as Kanthal[®] APM. The cup for the aluminium used in the "Aluminium Alloy Heating Simulation" and the graphite mould for the carbon textile preform were made from low porosity graphite.

ALUMINIUM ALLOY HEATING SIMULATION

At the beginning of the GPI manufacturing process in the designed furnace, an aluminium alloy is melted in the chamber thanks to radiant heaters. For the 226D alloy, the starting point of the material phase transition is its solidus temperature (T_s), which equals 833.15 K (560°C). During the numeric simulations, the authors focused on obtaining information about the time of the aluminium heating process necessary to achieve this temperature. To simplify the calculations, it was decided to use a 2D mesh model of the furnace chamber and of the elements inside (Fig. 4b and 4c), which was justified by their approximately symmetric geometry, presented in Figure 4a.
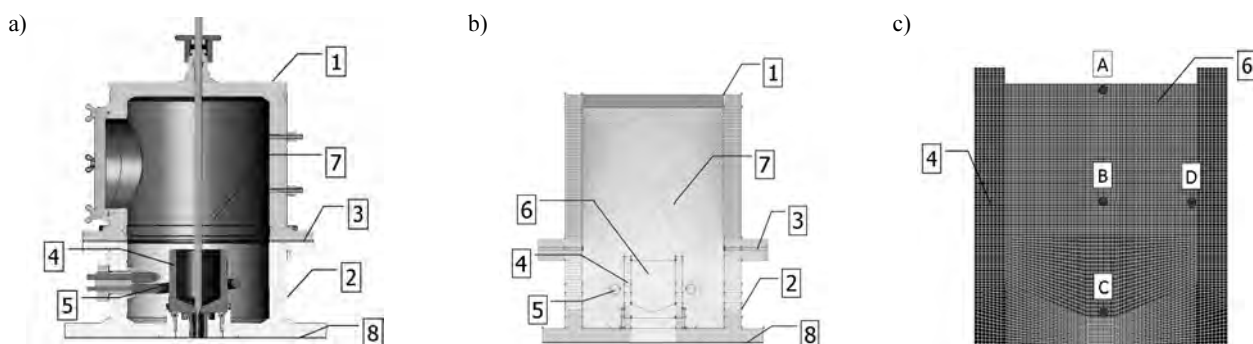

Fig. 4. Melting chamber: a) cross-section of geometry; b) quadratic/triangle mesh for simulations; c) mesh model of aluminium alloy inside graphite cup; 1 - top housing; 2 - bottom housing; 3 - graphite seal; 4 - graphite cup for aluminium alloy; 5 - radiant heater; 6 - aluminium alloy; 7 - vacuum phase; 8 - external wall joined to injection chamber; (A-D) - temperature measurement points

Rys. 4. Komora topienia: a) przekrój wzdłużny; b) siatka do symulacji składająca się z kwadratowych i trójkątnych elementów; c) model siatki stopu aluminium we wnętrzu grafitowego kubka; 1 - górna pokrywa; 2 - dolna pokrywa; 3 - uszczelka grafitowa; 4 - grafitowy kubek na materiał stopu aluminium; 5 - grzałka promieniująca; 6 - stop aluminium; 7 - próżnia; 8 - zewnętrzna ściana połączona z komorą wtryskiwania; (A-D) - punkty pomiaru temperatury

Boundary conditions

The numeric simulations of the aluminium alloy heating process required a model of the radiation heat transfer. In order to obtain it, an *S2S* ("Surface to Surface") model was chosen for the calculations. The following operating conditions were defined: pressure inside the heating chamber 0.1 Pa; gravity constant - 9.81 m/s^2. At the beginning of the calculations, the temperature of all the solid elements was equal to 293.15 K (20°C) except for the heater, which was around 993.15 K (720°C).

There were two investigated cases; with and without thermal interaction with the environment (relatively cold air) around the heating chamber. In the first case, all the external walls of the model were adiabatic (no thermal exchange between them and surrounding air). In the second simulation, the phenomenon of natural convection was considered.

Adiabatic external walls of melting chamber

The first step of the analysis was to compare the temperature curves (as a function of time) of four defined measurement points (A-D) of the aluminium alloy shown in Figure 4. It was observed that the temperature differences between the points were relatively small in comparison to the measuring range in the whole chamber. As an example, the temperature change is presented for point B (Fig. 5). An investigation of the findings showed that the required temperature was obtained after 6 hours and 4 minutes.
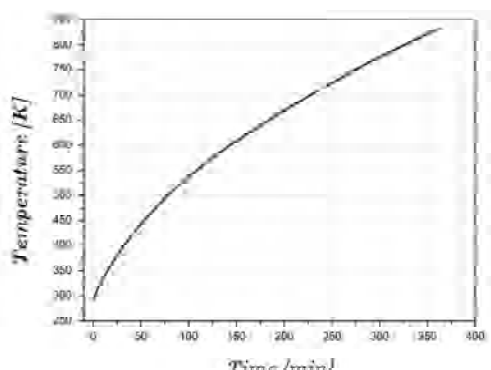

Fig. 5. Temperature variation as function of time of carbon textile preform at measurement point B

Rys. 5. Zmiana temperatury w czasie dla stopu aluminium w punkcie pomiarowym B

Natural convection case study

In the previous case, the external walls of the melting chamber were defined as adiabatic. In the real heating process, these walls are surrounded by air whose temperature is around 293 K (20°C). As a consequence of the natural convection process, the external walls are cooled down and the process of heating is predicted to last longer. For that purpose, it was necessary to determine the *Heat Transfer Coefficient* (α) according to equation.

$$\alpha = \frac{Nu \cdot \lambda}{L} \qquad (1)$$

where: α - heat transfer coefficient, W/m$^2 \cdot$K; λ - thermal conductivity coefficient, W/m$\cdot$K; Nu - nusselt number.

The calculations of the above equation provided different values of average heat transfer coefficients for each wall dependent on the wall thickness. The results mainly depended on the measured characteristic length as well as the shape and the orientation of the considered wall.

Results

The first step of the result analysis consisted in determining the temperature curves as a function of time for the heated aluminium alloy (Figure 6). It turned out that the solidus temperature 833 K (560°C) was not obtained (only 634 K = 361°C) even after 6 hours of continuous heating when the heater temperature equalled 993 K (720°C) and the phenomenon of natural convection on the external walls was considered. The observed effect is presumably the result of the relatively cold air around the chamber. It is suspected that the following improvements might solve this problem:
- increase maximum temperature of the heater,
- change chamber shape (heat transfer coefficient considerably depends on shape of the element),
- change chamber material,
- use isolation for the chamber.

Firstly, it was decided to increase the heater temperature to the maximum value of 1473.15 K (1200°C). The comparison of the heating processes for the above-mentioned cases is presented in Figure 6.
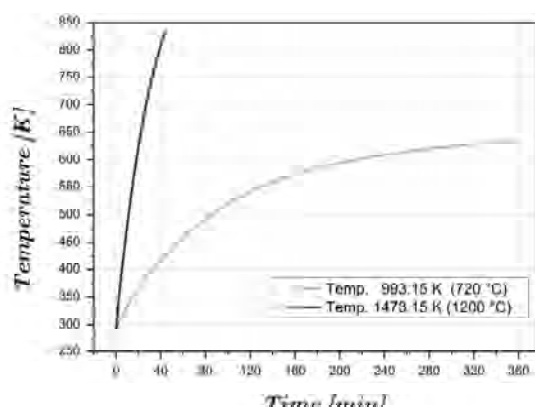

Fig. 6. Temperature variations as function of time for aluminium alloy 226D at measurement point B for two temperatures of heater

Rys. 6. Przebiegi czasowe krzywych temperaturowych dla stopu aluminium 226D w punkcie pomiarowym B przy dwóch zadanych temperaturach grzałki

As a result of this modification, the necessary temperature was reached after approximately 44 minutes (Figs 6 and 7).

A penetrating analysis indicated that a temperature equal to 833 K (560°C) was obtained at the measurement points in the following time order (from the first to the last one): D, B, A, C. The time between points D and C was equal to 36 seconds. In order to confirm the observed result, temperature maps were created from which four selected ones are presented in Figure 8.

CARBON TEXTILE PREFORM HEATING SIMULATION

The second manufacturing step of the MMC material in the investigated furnace is the heating of the carbon preform. It takes place in the injection chamber shown in Figure 9. With the aim of assessing a new design of the chamber, it was necessary to collect information about the heating time of the preform (a carbon fibre textile) from 293 K (20°C) to:

- 833 K (560°C),
- 873 K (600°C).

The approximately symmetric geometry of the considered model (Fig. 9a) enabled the use of a 2D mesh model (Fig. 9b).

Boundary conditions

Analogue to chapter 3, an *S2S* ("Surface to Surface") model was used. The following operating conditions were defined: pressure inside the injection chamber 0.1 Pa; gravity constant - 9.81 m/s². At the start of a calculation, the temperature of all the solid elements was equal to 293.15 K (20°C) except for the heater, in which it was 993.15 K (720°C).
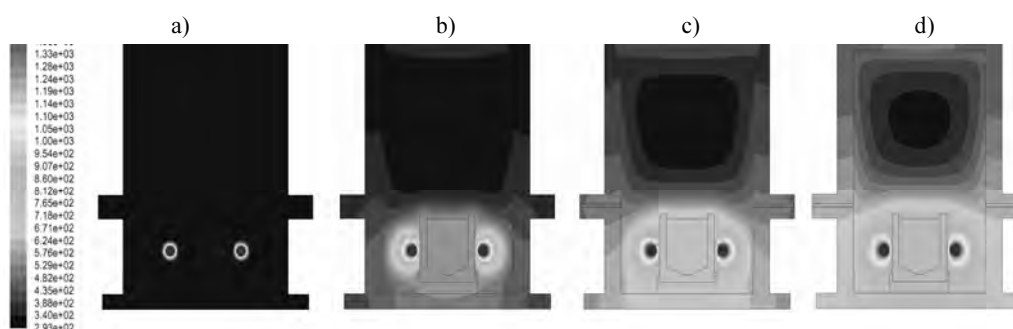

Fig. 7. Aluminium alloy heating process - maps of temperature (K) after: a) 10 seconds; b) 15 minutes; c) 30 minutes; d) 44 minutes of heating process

Rys. 7. Przebieg procesu nagrzewania stopu aluminium - mapy temperaturowe (K) po: a) 10 sekundach; b) 15 minutach; c) 30 minutach; d) 44 minutach procesu nagrzewania
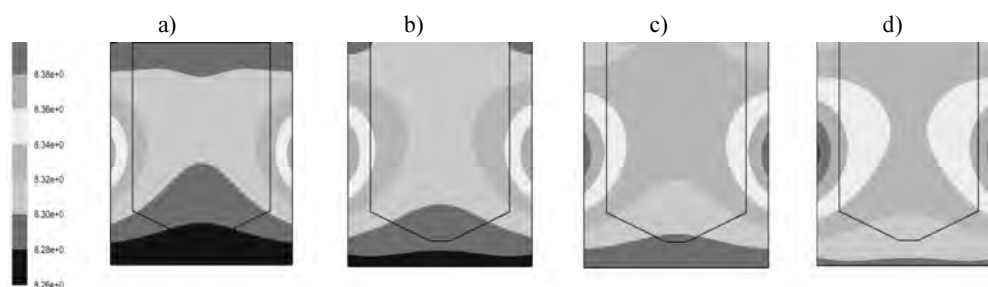

Fig. 8. Graphical presentation of temperature (K) change in time for graphite cup and aluminium alloy after: a) 43 minutes 33 seconds; b) 43 minutes 45 seconds; c) 43 minutes 57 seconds; d) 44 minutes 9 seconds of heating process

Rys. 8. Graficzna prezentacja zmian temperatury (K) w czasie dla grafitowego kubka, wypełnionego materiałem stopu aluminium, po: a) 43 minutach 33 sekundach; b) 43 minutach 45 sekundach; c) 43 minutach 57 sekundach; d) 44 minutach 9 sekundach procesu nagrzewania
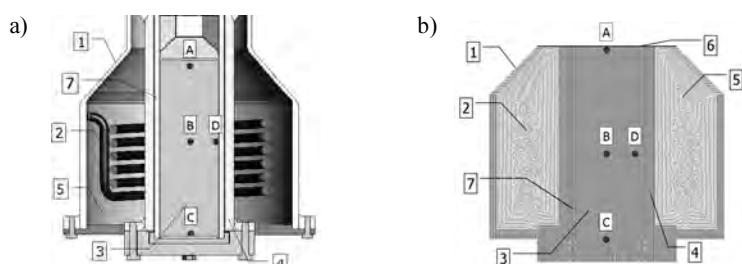

Fig. 9. Textile preform preheating chamber: a) cross-section of geometry; b) quadratic/triangle mesh for simulations; 1 - chamber housing; 2 - heaters; 3 - carbon textile preform; 4 - interior housing; 5 - vacuum phase; 6 - external wall joined to melting chamber; 7 - graphite mould; (A-D) - temperature measurement points

Rys. 9. Komora nagrzewania preformy z włókien węglowych: a) przekrój; b) siatka do symulacji składająca się z kwadratowych i trójkątnych elementów; 1 - obudowa komory; 2 - grzałki; 3 - preforma z materiału z włókien węglowych; 4 - wewnętrzna obudowa; 5 - próżnia; 6 - zewnętrzna ściana łącząca z komorą stapiania; 7 - forma grafitowa; (A-D) - punkty pomiaru temperatury

Similarly to the simulation of the aluminium alloy heating process, two cases were investigated - adiabatic external walls and the phenomenon of natural convection.

Adiabatic external walls

At the beginning of the result analysis, a comparison of the temperature vs. time curves, for all the measurement points (A-D), was made. During the research it was observed that temperature changes were almost the same for all the points compared to the measuring range, so that a representative variation is presented only for point B, see Figure 10. According to the Figure, the following temperatures were obtained:
- 833 K (560°C) - after 1 hour 20 minutes
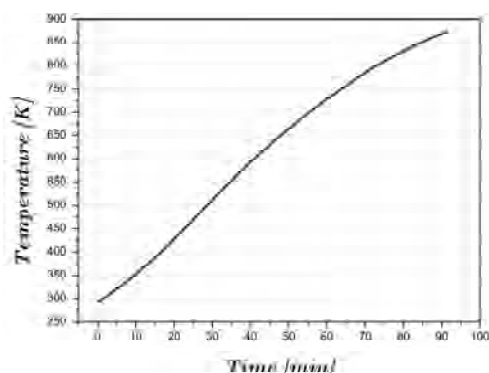- 873 K (600°C) - after 1 hour 31 minutes

Fig. 10.   Temperature variations as function of time for carbon textile preform at measurement point B

Rys. 10.   Zmiana temperatury w czasie dla preformy z włókien węglowych w punkcie pomiarowym B

Natural convection case study – results

At the beginning, temperature curves (as a function of time) of four measurement points (A-D) were determined (Fig. 11). In the case of the heater temperature equal to 993 K (720°C), the process of heating lasted successively:
- to 833 K (560°C) - 1 hour 45 minutes,
- to 873 K (600°C) - 2 hours 12 minutes.

The attained information shows that the phenomenon of natural convection has a significant influence on the time of heating in the designed furnace for the GPI manufacturing process of the MMC. In the case of a composite production, the setup time for the carbon textile preform should not be longer than the time of the aluminum alloy melting process. Therefore, a higher temperature of the heater, around 1473 K (1200°C), was applied and checked. The results of that correction are presented in Figure 11.
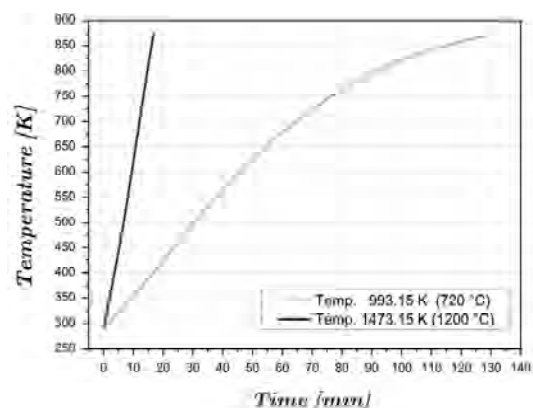

Fig. 11.   Temperature variations as function of time for carbon textile at measurement point B for two temperatures of heater

Rys. 11.   Przebiegi krzywych temperaturowych w czasie dla preformy z włókien węglowych w punkcie pomiarowym B, przy dwóch zadanych temperaturach grzałek

An increase of the heater temperature caused a decrease of the necessary setup time:
- to 833 K (560°C) - 16 minutes,
- to 873 K (600°C) - 17 minutes 10 seconds.

To confirm the results from the measurement points, temperature maps were created. Four of them are presented in Figure 12. A detailed analysis indicated that both required temperatures were obtained at the measurement points in the following time order (from the first to the last one): D, B, A, C, the time between point D and point C was 30÷32 seconds. A graphical presentation of the temperature change in the carbon textile preform is shown in Figure 13.
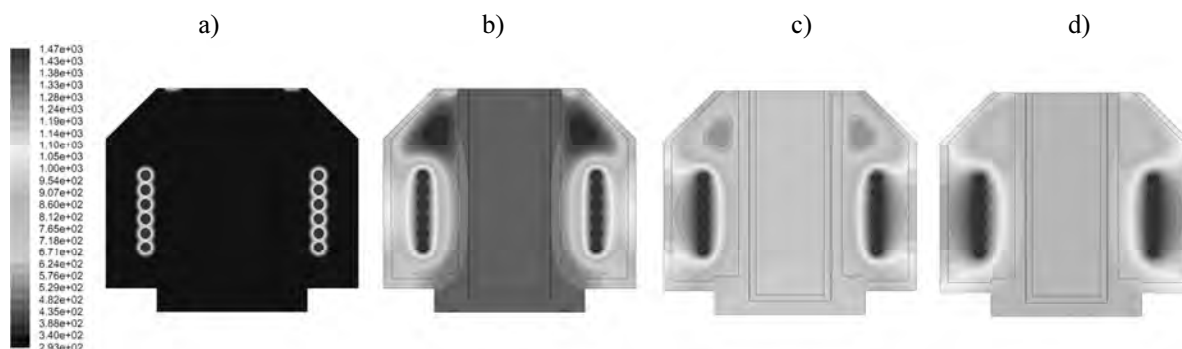

Fig. 12. Carbon textile preform preheating process - temperature maps (K) after: a) 10 seconds; b) 5 minutes 50 seconds; c) 11 minutes 30 seconds; d) 17 minutes 10 seconds of heating process. Heater temperature is 1473 K (1200°C)

Rys. 12. Przebieg procesu grzania preformy z włókien węglowych - mapy temperaturowe (K) po: a) 10 sekundach; b) 5 minutach 50 sekundach; c) 11 minutach 30 sekundach; d) 17 minutach 10 sekundach procesu grzania. Temperatura grzałek równa 1473 K (1200°C)
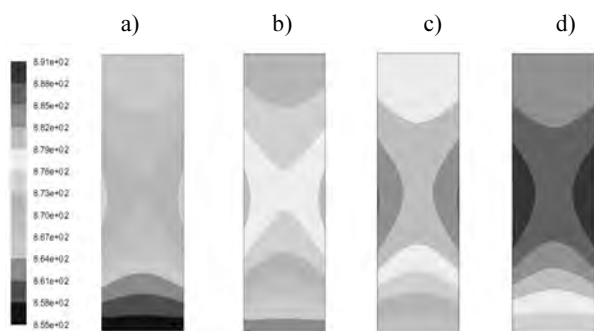
a)   b)   c)   d)

Fig. 13. Propagation of temperatures (K) in carbon textile preform - temperature maps after: a) 43 minutes 33 seconds; b) 43 minutes 45 seconds; c) 43 minutes 57 seconds; d) 44 minutes 9 seconds of heating process. Heater temperature is 1473 K

Rys. 13. Zmiany temperatury (K) preformy z włókien węglowych - mapy temperaturowe po: a) 43 minutach 33 sekundach; b) 43 minutach 45 sekundach; c) 43 minutach 57 sekundach; d) 44 minutach 9 sekundach procesu grzania. Temperatura grzałek równa 1473 K (1200°C)

CONCLUSIONS

Gas pressure infiltration technology enables one to fabricate complex carbon aluminium composites with fibre or textile reinforcement using precise graphite moulds. Generally, UD- and BD-specimens exhibit good infiltration results, with homogeneous fibre distribution and good surface quality, particularly thanks to the use of electrochemically Ni-coated fibres. However, during multiple infiltration tests with the aid of the existing equipment at ILK, disadvantages of the used GPI-unit became obvious. The drawbacks, such as: long duration of the process preparation, long duration of the infiltration process, combined heating of the preform and alloy, cooling of the MMC via the autoclave (low cooling rates) and limited control of the process, directly affect the mechanical properties of the manufactured planar specimens.

To face up to these challenges, a new furnace for a modified gas pressure infiltration technique was developed. Finite elements simulations lead to the conclusion that the heaters chosen for the furnace chambers are able to heat the aluminum alloy and the carbon textile prefom to the required temperatures in acceptable times, although it depends on the heating conditions. Furthermore, the simulations showed the significance of the natural convection phenomenon and isolation between the furnace and its environment. The new versions of the GPI-oven enable one to accelerate the process of heating in both cases. Finally, the numerical calculations of the heating process formed the basis for future simulations of both the aluminium alloy melting process and solidification of the manufactured MMC based on carbon fibres.

Acknowledgement

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