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MANUFACTURING WITH APPLICATION OF GPI METHOD AND SELECTED PROPERTIES OF Al MATRIX COMPOSITES REINFORCED UNIDIRECTIONALLY AND THREE-DIRECTIONALLY WITH CARBON FIBRES

WYTWARZANIE METODĄ INFILTRACJI GAZOWEJ I WYBRANE WŁASNOŚCI KOMPOZYTÓW NA OSNOWIE ALUMINIUM, UMOCNIONYCH JEDNO I TRÓJKIERUNKOWO WŁÓKNAMI WĘGLOWYMI

The discussion of the possibility of application of the GPI (gas pressure infiltration) process to the manufacturing of composites based on selected aluminium alloys reinforced with carbon fibres coated with nickel protective layer, as well as the determination of selected properties of materials obtained using this technique, is presented in the article. The composites reinforced unidirectionally (UD) were produced, the suitable volume fraction of fibres was determined and the proper forming parameters were established. Basing on the obtained results, with application of the same components, the composites reinforced three-directionally (3D) were subjected to infiltration. The preforms were designed and prepared using plaiting and joining methods. The GPI process parameters were verified for the assumed fibre arrangement. Thermal expansion of matrix alloys and composites obtained with application of most favourable parameters was determined and the influence of fibre arrangement and chemical composition of the matrix on the obtained results was analysed. The comparative abrasion tests with application of different velocities were performed for the selected alloy and the composite reinforced unidirectionally. In order to evaluate the changes taking place in the matrix during infiltration, the analysis of chemical composition of composites was performed for materials reinforced unidirectionally, as an example. The correctness of distribution of fibres in the composite matrix was also evaluated by means of microstructure observation as well as non-destructive testing with application of computed tomography technique. The results obtained during the investigations provide information concerning suitability and limitations of the GPI method to the manufacturing of light structural parts from the proposed components.

Keywords: aluminium matrix composites, carbon fibres, gas pressure infiltration, autoclave, microstructure, dilatometry, wear resistance, non-destructive testing

W pracy podjęto próbę oceny możliwości stosowania procesu infiltracji gazowej do wytwarzania kompozytów na osnowie wybranych stopów aluminium, umocnionych włóknami węglowymi pokrytymi warstwą ochronną niklu a także określenia wybranych właściwości otrzymanych w ten sposób materiałów. Wykonano kompozyty umocnione jednokierunkowo, określono odpowiedni dla nich udział objętościowy włókien i wyznaczono właściwe parametry ich formowania. W oparciu o otrzymane wyniki oraz stosując te same komponenty przeprowadzono proces infiltracji kompozytów umocnionych trójkierunkowo. Do tego celu zaprojektowano i przygotowano preformy z wykorzystaniem metod wyplatania oraz łączenia. Parametry procesu GPI zweryfikowano dla tak przyjętego układu włókien. Określono rozszerzalność termiczną stopów osnowy oraz kompozytów otrzymanych przy zastosowaniu najkorzystniejszych parametrów, ocenie poddano wpływ ułożenia włókien oraz składu chemicznego osnowy na otrzymane wyniki. Dla wybranego stopu i otrzymanego na jego osnowie kompozytu umocnionego jednokierunkowo wykonano porównawcze badania odporności na zużycie ścierne, które prowadzono przy różnej prędkości realizacji testów. W celu oszacowania zmian zachodzących w osnowie podczas infiltracji wykonano na przykładzie tworzyw umocnionych jednokierunkowo analizę składu chemicznego kompozytów. Ocenie poddano także poprawność rozlokowania włókien w osnowie kompozytów, prowadząc w tym celu obserwacje mikrostruktury oraz badania nieniszczące z wykorzystaniem metody tomografii komputerowej. Otrzymane podczas badań wyniki stanowią informację na temat przydatności i ograniczeń w stosowaniu metody GPI do wytwarzania z zaproponowanych komponentów elementów lekkich konstrukcji.

1. Introduction

Composites based on light metals or alloys reinforced with continuous fibres find their application in the construction of modern structures, mainly in automotive, aircraft and defence industries, but also in sports and recreation areas. Through the proper selection of fibres distribution pattern it is possible to adjust the reinforcement mode to the loading conditions occurring during working of an element [1,2]. In case, when the element is carrying longitudinal loads, unidirectional distribution of fibres in the matrix is favourable. Complex stress state requires the application of two- or three-directional

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fibre distribution pattern. From among the materials being discussed, composites based on aluminium alloys reinforced with continuous carbon fibres (CF/Al-MMC) are some of the most attractive ones. In recent years, more and more researchers have been interested in interface bonding, fibres dispersion and fabrication process of these composites [3-7]. Low density of aluminium alloys as well as their relatively low price in comparison with the alloys of other light metals such as magnesium or titanium, are convincing arguments for their application as a matrix material. Carbon fibres have been among the perfect candidates for composite reinforcement due to their high specific strength, good flexibility, high elastic modulus, low expansion coefficient, good thermal conductivity and especially the light weight [5,8-11]. Low price and availability of this fibres, when compared, for example, with ceramic fibres, make them a preferred choice for the application as a reinforcing phase. Among the most important advantages of such combination of components are the stability of dimensions and properties of products at elevated temperatures as well as their wear resistance [1,2,6,12]. However, regardless of the specified advantages, some problems arise during manufacturing of aluminium alloy – carbon fibres composites. These problems, if not resolved, limit the possibility of mass production of such composites and influence unfavourably the properties of products. The first issue is a fact that carbon fibres can be hardly wet by a liquid aluminium. Since the processes mostly applied to the manufacturing of these composites proceed in liquid-phase conditions [13-15], problems arise, as a consequence, to obtain suitable quality bonding between components. The other limitation are unfavourable chemical reactions proceeding at the boundary between a matrix and a fibre at the temperature necessary for melting of a matrix [16,17], especially the reaction resulting in the formation of a brittle Al_4C_3 phase.

On the basis of the problem analysis and own research work, a few methods can be proposed to limit or resolve the specified problems. The first one is based on the modification of a chemical composition of the matrix, through the selection of suitable alloying components, in order to improve the wetting angle and/or to limit unfavourable reactions at the phase boundary [2,17]. The limited reactivity can be achieved by introducing at least 7% of silicon into the alloy, which significantly decreases the tendency to form aluminium carbide at the interface. The similar effect can be obtained by introducing magnesium or titanium into the matrix. The introduction of strontium, titanium and magnesium into the matrix leads to the decrease of wetting angle [1,17]. The specified problems can be eliminated also by coating carbon fibres with a protective layer. Nickel or copper coatings are mostly used for this purpose [2,18,19]. The other solution is a selection of a proper forming technology, with a purposeful determination of its parameters resulting in a limited reactivity of components and/or decreased wetting angle. The example technology is a GPI process [2,6,14,20-22]. The possibility of controlling the process parameters in a wide range, including temperature, pressure and contact time of a liquid phase with fibres, allows to establish such combination of parameters which, for the assumed chemical composition of components, will lead to obtaining high-quality composites.

2. Objective and scope of research

The objective of the research work was the analysis of the influence of a chemical composition of the matrix, the infiltration parameters and fibre distribution on the microstructure and selected properties of composites based on aluminium alloys reinforced with carbon fibres, coated with nickel protective layer.

Composites reinforced unidirectionally (UD) were manufactured, suitable volume fraction of fibres was determined and favourable forming parameters were established. Basing on the obtained results, the 3D reinforced composites reinforced were subjected to infiltration, applying the preforms prepared using braiding and joining methods. The GPI process parameters were verified for the assumed fibre arrangement. Selected properties of materials obtained with application of most favourable infiltration parameters were determined and compared. The quality of distribution of fibres in the composite matrix was evaluated by means of metallographic examination as well as testing with application of computed tomography technique.

3. Fabrication of the CF/Al-MMC

3.1. Raw materials

Aluminium alloys, trade names Trimal 05 (TR05) and Trimal 37 (TR37), were used as matrix materials. The chemical composition of Trimal alloys is given in Table 1 [23]. Commercial carbon fibres Tenax-J HTS40 manufactured by Toho Tenax, coated with 0.25 μm nickel protective layer, were used as a reinforcing phase. The fibres were applied in a form of a bundle containing 12,000 pieces. Selected properties of carbon fibres [24] are collected in Table 2. Figure 1 presents the picture of fibres made during own investigations, with protective layers visible on lateral surfaces.

TABLE 1

Chemical composition of Trimal 05 and Trimal 37 alloys

Material		Si	Fe	Cu	Mn	Mg	Mo	Zr	Zn	Ti	V	Others	Bal
TR05	min.	8.5		0.1	0.3		0.1	0.1			0.03		Al
	max.	10.5	0.15	0.2	0.6	0.08	0.3	0.3	0.07	0.06	0.1	0.15	Al
TR37	min.	9.5			0.4	0.1				0.03			Al
	max.	11.0	0.26	0.05	0.7	0.4			0.07	0.12		0.2	Al

TABLE 2
Selected properties of carbon fibres

Density, g/cm^3 %	Diameter, μm	Tensile strength MPa	Young's modulus, GPa	Elongation at break
2.7	7.5	2750	215	1.2

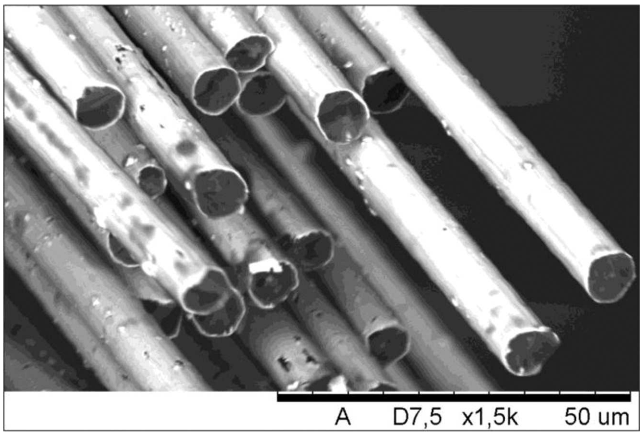

Fig. 1. Morphology of carbon fibres Tenax-J HTS40 coated with nickel protective layer

3.2. Preparation of test specimens by means of GPI method

The preparation of test specimens by means of Gas Pressure Infiltration Process (GPI) was carried out at the Institute of Lightweight Structures and Polymer Technology – ILK, Technische Universität Dresden. The autoclave test stand was applied, offering the possibility to control process parameters such as temperature, heating and cooling rates, holding time and gas pressure during infiltration, as well as to carry out the selected process stages in vacuum conditions. This allows to establish a favourable combination of the above mentioned parameters.

3.2.1. Preparation of specimens reinforced unidirectionally (UD)

The manufacturing of UD reinforced specimens involved the preparation and infiltration of preforms. At first, specimens were wound onto a frame, using winding device that enables programming of parameters for that operation. One pass was realized, with a linear displacement of the frame equal to 65 mm. The number of revolutions of the frame resulted from the assumed volume fraction of fibres in the composite matrix. The infiltration was performed using a set of graphite moulds consisting of the internal and the external mould. In order to protect the purity of the alloy, the moulds were coated with boron nitride protective layer. The fibres were taken off the frame and put into the internal mould. Figure 2 presents the moulds after coating with boron nitride protective layer.

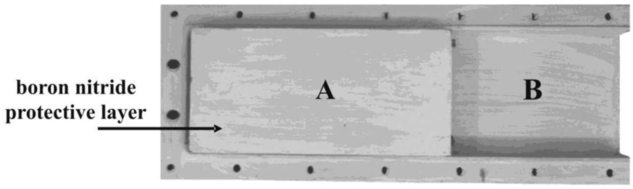

Fig. 2. Graphite moulds for infiltration: A – internal mould, B – external mould

Both moulds were assembled and the matrix alloy of a suitable volume was put into the external mould. The whole assembly was placed and closed in the autoclave chamber and then subjected to gas pressure infiltration under controlled conditions. During the infiltration process, the real-time changes of essential parameters were observed and recorded. The example results are presented in Figure 3. Consecutive stages of specimen preparation are shown schematically in Figure 4.

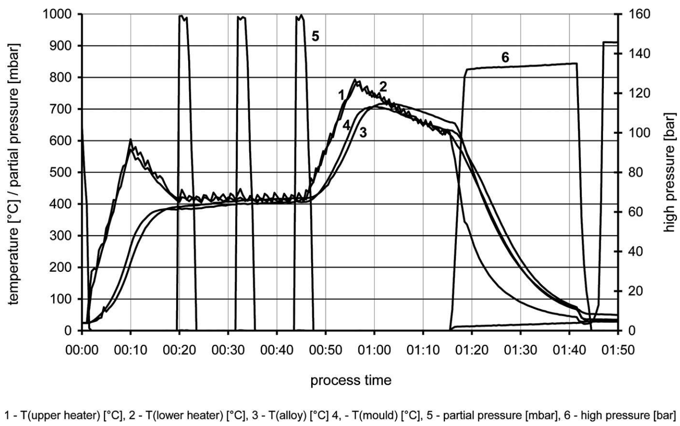

Fig. 3. The example of parameter changes during the GPI process, recorded when manufacturing TR37-based UD composite reinforced with 30% of carbon fibres

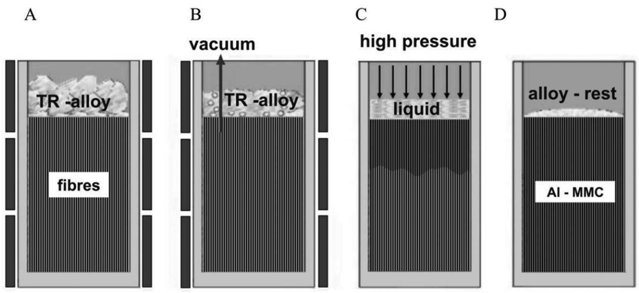

Fig. 4. Stages of manufacturing of TR alloy–carbon fibres composites via of GPI method: A – preliminary heat treatment at the temperature of 400°C, with cyclic ventilation of chamber, B – heating to the temperature above liquidus temperature of the alloy, under vacuum conditions, C – infiltration of the preform under high gas pressure, D – cooling

The proposed composite manufacturing process consisted of four basic stages. The preliminary heat treatment stage (Fig. 3 and 4A), lasting for about 45 minutes, aimed at the removal of a standard polymer sizing, spread on fibres' surface at the time of their manufacturing [24]. The sizing makes it easier to bond the components when manufacturing polymer composites. In case of metal alloys used as a matrix, the polymer sizing proves to be disadvantageous, as it evaporates during the process, and its presence in gaseous state additionally impairs the wettability of fibres by a liquid alloy. Therefore, the sizing has to be removed by combustion at the temperature of 400°C, with simultaneous cyclic ventilation of autoclave chamber in order to supply the oxygen necessary for combustion and remove combustion products. Three ventilation cycles were applied during the investigations (Fig. 3), which is sufficient for sizing removal. The actual infiltration process began with heating of the assembly under vacuum conditions to the temperature higher than liquidus temperature of the matrix alloy and holding at that temperature for a time necessary for complete meltdown of the alloy (Fig. 4B). Next, argon was introduced under high pressure into the autoclave chamber, in order to force the liquid metal into the preform causing its infiltration (Fig. 4C). In the last stage (Fig. 4D) the autoclave chamber was ventilated with argon, which enabled cooling of the composite under protective atmosphere conditions.

It should be noticed that during the realisation of the second stage, i.e. melting and holding the alloy at a specified temperature, a natural infiltration is possible, depending on wetting angle between fibres and a liquid alloy. In such case, it would be aimless to use a complicated GPI method for the analysed components. Taking this into account, a test was performed omitting the stage of introducing the gas under high pressure into the chamber, while the other process parameters remained unchanged. It was found that under the given conditions the liquid alloy did not infiltrate the fibres, which indicates the unfavourable value of wetting angle between the applied components, thus justifying the use of GPI technique in this case.

The preparation of specimens using the GPI process was realized with application of different matrix materials, varying volume fraction of fibres in the composite matrix and varying infiltration time. The investigations were carried out in stages, by the preliminary quality assessment of specimens obtained under the given conditions. The conditions assumed for individual stages are collected in Table 3.

TABLE 3
Scheme of specimens manufacture using the GPI method

Stage	Alloy	vol% of fibres	GPI time, min	Quality
I	TR37	30	20	good
	TR37	37	20	bad
II	TR37	30	15	bad
	TR37	30	25	medium
III	TR05	30	20	good
IV	TR05	0	20	medium
	TR37	0	20	medium

In the stage I, the preforms were used containing 30% of fibres as well as 37%, which was the maximum volume fraction of fibres attainable for one pass realized during winding. In the discussed stage, TR37 was the matrix alloy, and the process was realized with constant parameters. In case of 37% of fibres, their packing was too dense and thus it was not possible to fully infiltrate the preform with a liquid alloy. Bundles of fibres were visible on the surface of the obtained specimen. In case of 30% of fibres, the experiment was successful. During the stage II, different times of heating of a matrix alloy were tested (Table 3). The variant assuming 15 minutes of heating time proved to be unsuccessful. In case of a longer heating time, the infiltration did not take place at the edges of the mould. In the stage III, applying the parameters that proved to be favourable for TR37 alloy, the infiltration of a preform with TR05 alloy was also performed successfully. For a comparison, in the stage IV the process of pouring the empty internal mould with TR05 and TR37 alloys was realized, applying the parameters established as favourable ones in stages I-III. As a result, unfilled regions at the edges of internal mould were observed, which was caused by too intensive flow of the alloy, resulting from the realization of the GPI process with the empty internal mould, but under the conditions established as favourable ones during the preform infiltration. Basing on the quality assessment of specimens obtained in stages I-IV it was found that for the assumed components the suitable volume fraction of fibres in the matrix amounts to 30% and the appropriate time of infiltration is determined to be 20 minutes. For the composites manufactured as described above and, for comparison, for matrix alloys, testing of their selected properties was realized.

3.2.2. Manufacturing of composites reinforced three-directionally (3D)

The specimens of composites reinforced three-directionally were prepared using the GPI method, with application of the same initial materials as in case of composites reinforced unidirectionally. The preparation of 3D preforms from carbon fibres coated with nickel protective layer consisted of two stages, including the operations of braiding of reinforcement and joining the braided structures. In the first stage the bundles of carbon fibres were wound onto the spoons, which were then installed in a braiding machine, located at the ILK TU-Dresden, and finally a textile with bidirectional fibre arrangement was produced (Fig. 5). The textiles were semi-finished products, from which three-dimensional infiltration preforms were manufactured, according to the scheme presented in Figure 6. Rectangular textile pieces were cut out (Fig. 6A) and placed in pairs in suitably prepared frames (Fig. 6B). Then they were joined manually using fibre bundles being interleaved systematically through the textiles (Fig. 6C). This allowed to obtain preforms showing three-directional fibre arrangement. The structure and actual shape of a preform is presented in Figure 6D.

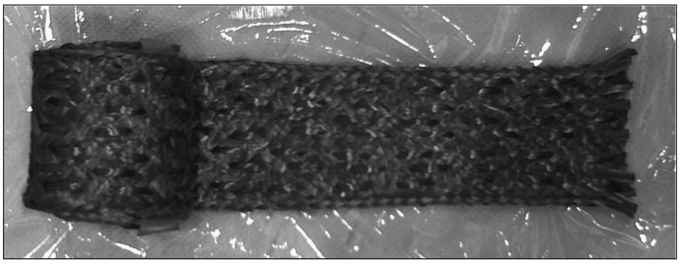

Fig. 5. Semi-finished product with bidirectional fibre arrangement obtained by means of plaiting

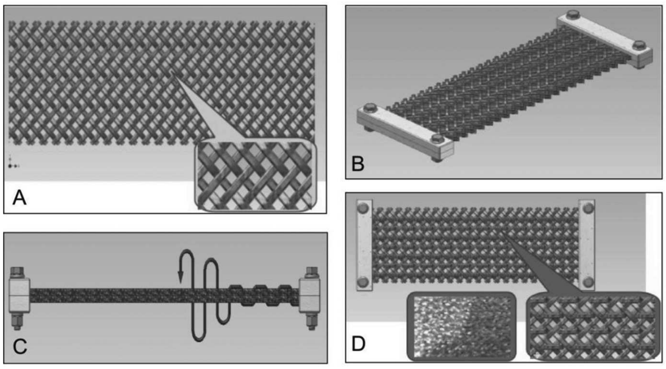

Fig. 6. Scheme of preparation of preforms: A – two-dimensional textile, B – placing the textiles in frames, C – joining the textiles with a fibre bundle, D – preform

The manufacturing of composites was realized by means of GPI method, making use of the same test stand and equipment which was employed to the preparation of unidirectionally reinforced composites. The alloys Trimal 05 and Trimal 37 were used as the materials for composite matrix. The volume fraction of fibres resulted from the assumed technique of preform preparation and the shape of internal mould, and amounted to 25%. Preliminary infiltration tests were carried out applying the parameters established to be favourable for the case of unidirectionally reinforced composites. However, the quality of the obtained specimens was low. It was found that process parameters, which were applicable to the manufacturing of composites from the preforms containing fibres arranged in parallel to the direction of liquid alloy flow forced by the gas pressure, do not guarantee satisfactory results in case of a complex fibre configuration such as the assumed three-directional arrangement. Therefore, basing on the experimental results, the process was modified at the stage of actual infiltration. The changes of the essential infiltration parameters after their adjustment to the assumed fibre arrangement, are presented in Figure 7. Favourable results were obtained through shortening of a cooling time after melting of the alloy, which led to the beginning of infiltration at the matrix temperature higher by about 50°C (see Fig. 3 and Fig. 7). The manufacturing of composites from 3D preforms with application of the GPI process under modified conditions allowed to correctly fill the mould, for both matrix alloys being applied, and made it possible to obtain high-quality composites.

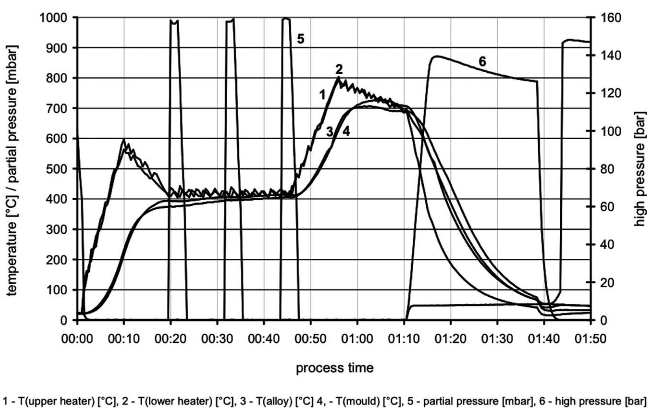

Fig. 7. The example of parameter changes during the GPI process, recorded when manufacturing 3D composite

4. Investigations of fabricated composites

Thermal expansion of matrix alloys and composites obtained using the most favourable infiltration parameters was determined and the influence of fibre arrangement and chemical composition of the matrix on the obtained results was estimated. Taking TR05 alloy as an example, as well as TR05-based composite reinforced unidirectionally, comparative investigations of wear resistance were performed, applying different test velocities. In order to evaluate the changes taking place in the matrix during infiltration, the simplified analysis of a chemical composition of composites reinforced unidirectionally, as an example, was performed. The correctness of distribution of fibres in the composite matrix was also evaluated by means of microstructure observation using a scanning electron microscope (SEM) as well as non-destructive testing with application of computed tomography technique

Dilatometry

Dilatometric testing was carried out for specimens of TR05 and TR37 alloys, as well as for composites reinforced unidirectionally and three-directionally, manufactured using the GPI process parameters established as favourable ones. The specimens with the dimensions 2×4×20 were used, where the major dimension corresponded with the direction of material flow during infiltration. The tests were realized within the temperature range up to 500°C. Figure 8 presents the diagrams

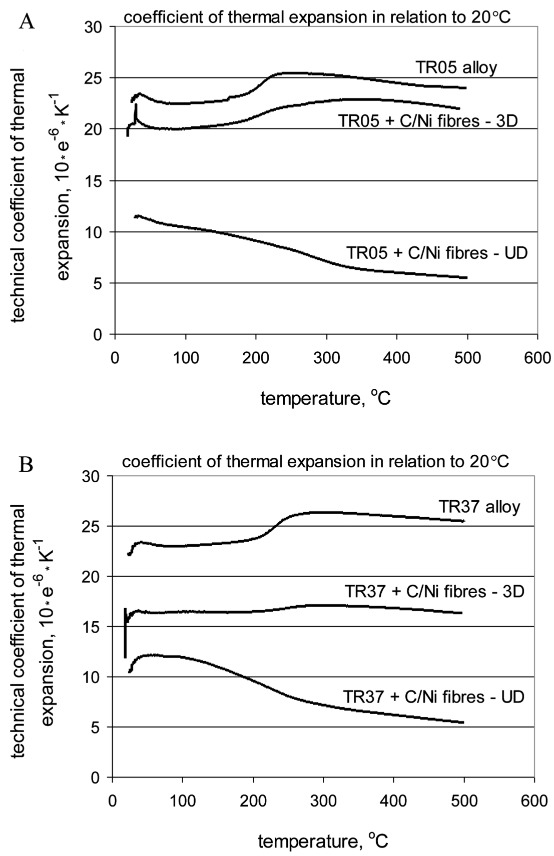

Fig. 8. The effect of a chemical composition of the matrix and the fibre arrangement on the coefficient of thermal expansion determined in the temperature range from room temperature up to 500°C, in relation to 20°C

illustrating the effect of the type of matrix alloy and the fibre arrangement on the variations of the coefficient of thermal expansion determined in the assumed temperature range, in relation to 20°C.

It was found that the relationships obtained for both non-reinforced alloys were quantitatively and qualitatively comparable. Introducing the fibres in 3D arrangement into the matrix resulted in only slight decrease of the coefficient of thermal expansion for the composite based on TR05 alloy (Fig. 8A), and its significant decrease in case of TR37-based material (Fig. 8B). Substantial lowering of the coefficient of thermal expansion was observed in case of composites reinforced unidirectionally (UD). The discussed effect was evident in the whole assumed range of temperatures (Fig. 8A,B), with the difference between the values of coefficients obtained for matrix materials and composites increasing with rising temperature.

Analysis of chemical composition

The EDS analysis was performed using Hitachi TM3000 scanning electron microscope. The example results of the analysis are presented in Fig. 9. The occurrence of nickel was detected both in areas adjacent to the fibres and in the composite matrix, which indicates the diffusion of nickel from protective coatings to the matrix. This may result in the degradation of coatings as well as in unwanted change of a chemical composition of the matrix, and finally, in impaired properties of composites.

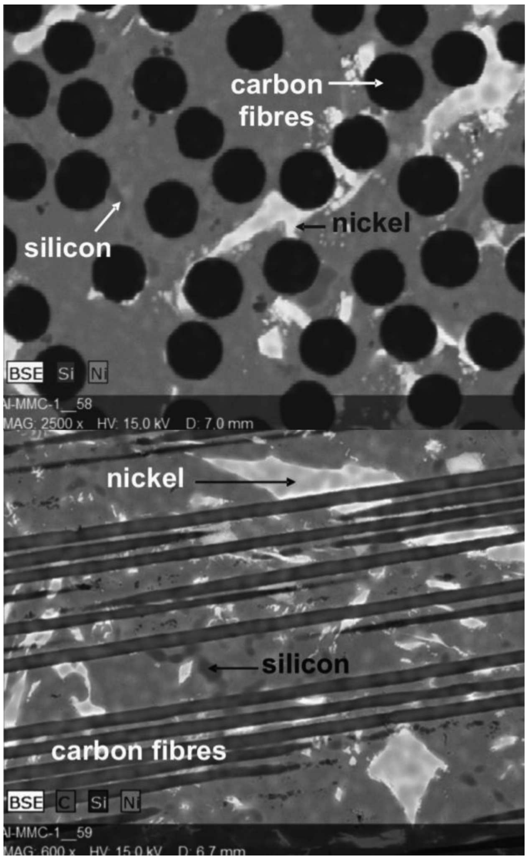

Fig. 9. Results of the simplified EDS analysis of chemical composition: A – Trimal 05, cross section, B – Trimal 37, longitudinal section

Wear resistance

Wear resistance testing was carried out for TR05 alloy and TR05-based composite reinforced with 30 % of carbon fibres. The tests were realized with application of a comparative test stand, at room temperature, applying friction path of 500 m and linear velocities of 0.4 and 1.0 m/s. During the tests, the composite specimens were fixed in a position enabling the grinding of a surface perpendicular to the direction of the arrangement of fibres in the matrix (Fig. 10). The specimen was subjected to pressure of 7 N against the lateral surface of a counter-specimen, which was a disk of 125 mm diameter, 1 mm thickness and hardness of 64 HRC. The results of wear resistance testing are collected in Fig. 10.

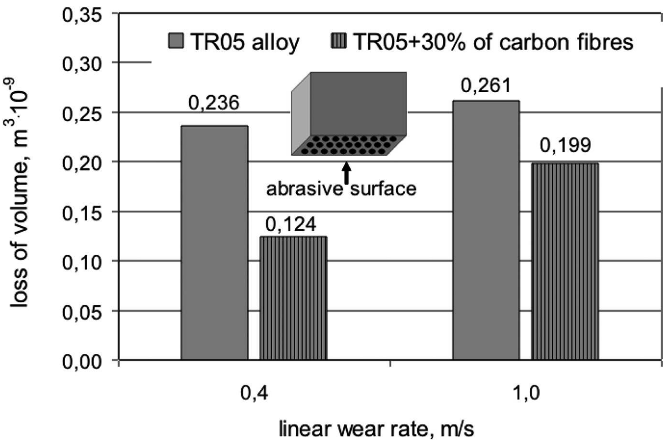

Fig. 10. Influence of linear velocity on wear resistance of TR05 alloy and TR05-based composite reinforced with 30% of carbon fibres, manufactured by means of the GPI process

Basing on the results of comparative tests, it was found that the introduction of 30% of fibres into the matrix resulted in only slight decrease of abrasive wear when applying the linear grinding velocity of 1.0 m/s. As a result of decreasing the velocity to 0.4 m/s, a significant drop of abrasive wear of a composite was observed, with only slight decrease of the wear of a matrix (Fig. 10). This was probably caused by the vibrations of the assembly, generated at higher velocity, resulting in percussive devastation of end faces of fibres. Stable and smooth operation of the assembly observed at lower velocity led to the increase of the role of fibres as a phase protecting the composite matrix from wear during grinding.

Metallographic examination

The observations of composite microstructure were carried out on polished sections, with application of scanning electron microscopy (SEM). Selected examples of a microstructure of composites reinforced unidirectionally are presented in Figure 11, while those representing composites with 3D fibre arrangement are shown in Figure 12.

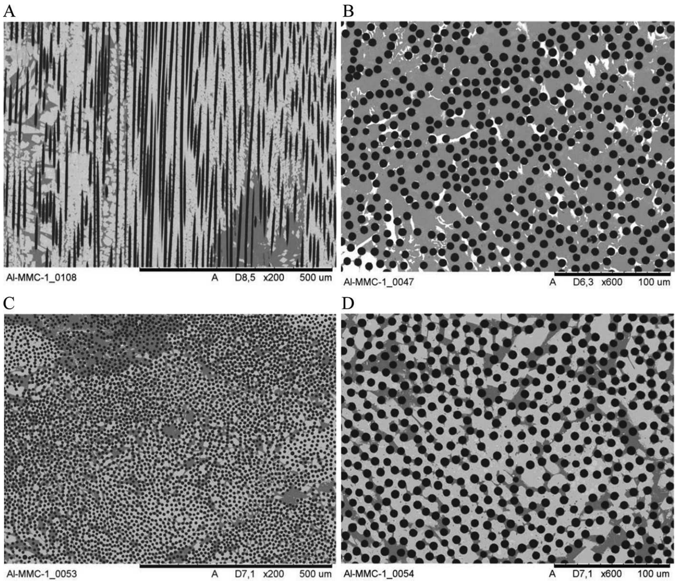

Fig. 11. Microstructure of composites based on TR05 (A,B) and TR37 (C,D) alloys, obtained as a result of gas infiltration of preforms with unidirectional fibre arrangement (UD). Polished sections, A – longitudinal section, B-D – cross-sections

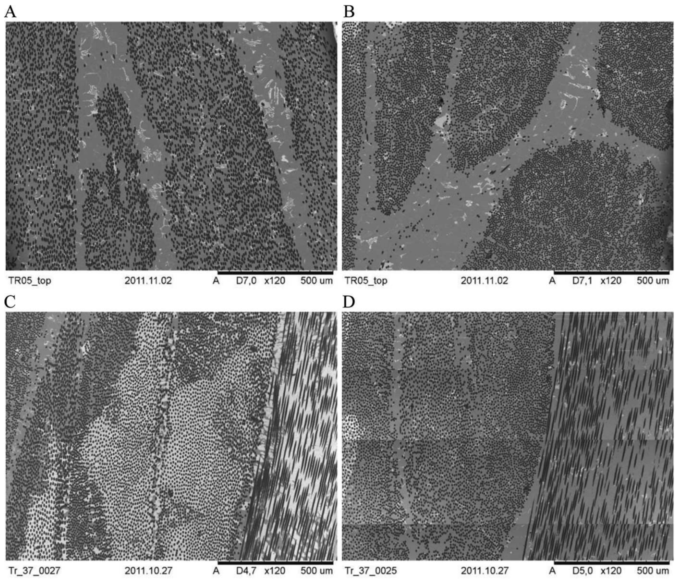

Fig. 12. Microstructure of composites based on TR05 (A,B) and TR37 (C,D) alloys, obtained as a result of gas infiltration of preforms with three-dimensional fibre arrangement. Polished cross-sections

In case of composites reinforced unidirectionally, containing 30% of fibres, uniform distribution of fibres in the matrix was observed, regardless of the applied aluminium alloy (Fig. 11). The fibres visible on longitudinal section showed continuity. No damages of fibres were found as a result of the flow of a liquid alloy into the preform, forced by a high gas pressure (Fig. 11A). In case of composites with three-directional reinforcement, the arrangement of fibres was determinated by the assumed technique of preform preparation and depended on the area of observation. Typical examples of configuration of fibre bundles in the matrix are presented in Fig. 12. The areas can be observed where the neighbouring bundles show similar (Fig. 12A-B) or different (Fig. 12C-D) orientation. In case of both methods of composite reinforcement (UD, 3D), no voids, discontinuities or conglomerates were found, and the individual fibres were isolated by the matrix, thus qualitatively confirming the proper selection of infiltration process parameters applied to the assumed shape of preform.

Non-destructive testing with application of computed tomography

The qualitative information concerning the internal structure of composites was obtained with application of non-destructive testing, using the computed tomography technique (CT). The tests were performed at the ILK TU-Dresden, employing v tome × 450 tomograph. Scanning was realized with a resolution of 10 μm. In case of composites reinforced unidirectionally, the specimens with the dimensions 2×4×20 mm were tested, with the major dimension corresponding with the direction of fibre arrangement in the preform. In case of composites reinforced three-directionally, the specimens with the dimensions 2×10×10 mm were prepared, which enabled the realization of CT scanning of the whole systematically repeated pattern of fibre arrangement in the preform. Three-dimensional view of a specimen obtained using CT technique, as well as the images showing the selected sections of a composite reinforced unidirectionally, are collected in Figure 13. Figure 14 presents the selected tomography results obtained for TR05 specimen reinforced three-directionally.

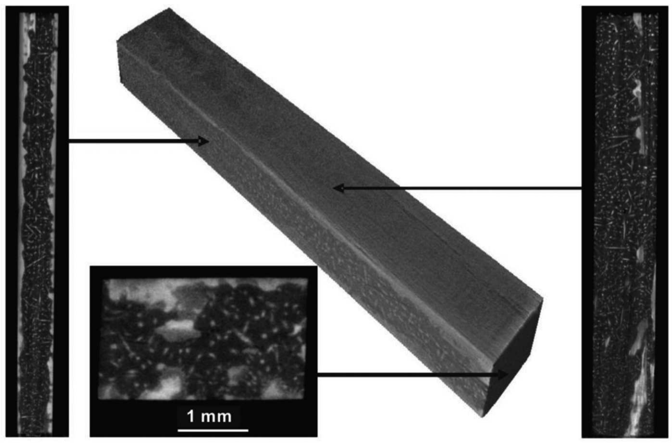

Fig. 13. Results of testing of TR37+30% composite with application of the computed tomography technique: three-dimensional image of a specimen and images of example sections in individual planes

The computed tomography of composites reinforced unidirectionally showed the occurrence of only sparse discontinuities, regardless of the chemical composition of the matrix (Fig. 13). In case of three-directionally reinforced composites (Fig. 14), the applied resolution allowed to detect sporadically occurring voids, mostly in the form of circular pores of a small size. Regardless of the fibre arrangement in the matrix, the bright areas are visible, which are the clusters of nickel coming from the protective coatings of carbon fibres.

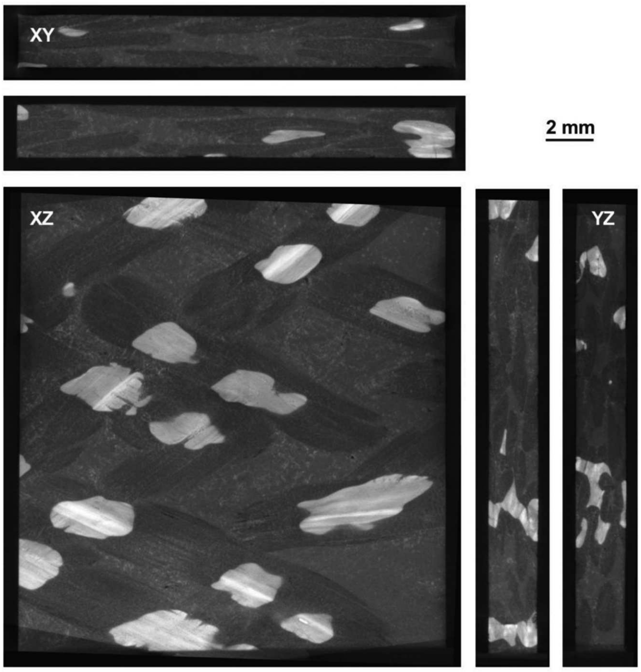

Fig. 14. Example images of the individual sections of TR05-based three-directionally reinforced composite, obtained using CT technique

5. Conclusions

In the light of the results of investigations of the influence of chemical composition of the matrix, infiltration process parameters and the arrangement of fibres in the matrix on the microstructure and selected properties of composites based on aluminium alloys, reinforced with carbon fibres coated with a nickel protective layer, it was found that:

1. The proposed gas infiltration method can be applied to the manufacturing of composites based on the analysed TR05 and TR37 alloys reinforced with carbon fibres, provided that a proper combination of process parameters is established.
2. It was found that in case of composites reinforced unidirectionally, the proper volume fraction of fibres amounted to 30%, and the adequate time of infiltration was 20 minutes. In order to obtain high-quality three-directionally reinforced composites, the modification of the GPI process was necessary, which was realized by starting the introduction of the gas under high pressure into the chamber at higher temperature of the alloy.
3. As a result of introduction of fibres into the matrix, a significant decrease of the technical coefficient of thermal expansion was observed for both alloys being analysed and in the whole range of temperatures applied in the tests.
4. Reinforcement of TR05 alloy with carbon fibres, with their positioning perpendicularly to the surface being ground, resulted in evident drop of abrasive wear, when compared with the matrix, observed at the lower one of two grinding velocities applied in the tests.
5. Diffusion of nickel from protective coatings to the matrix, observed after infiltration, causes the local changes of chemical composition of the matrix and may result in the degradation of nickel coatings protecting the fibres and, in consequence, in unfavourable reactions proceeding at the boundaries between components.
6. Microstructure observations and non-destructive testing realized with application of computed tomography showed the proper arrangement and uniform distribution of fibres in the matrix, as well as their continuity, thus confirming the proper selection of gas infiltration process parameters.

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