Archives of Materials Science and Engineering

Volume 80
Issue 1
July 2016
Pages 16-30

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

The structure and properties of aluminium alloys matrix composite materials with reinforcement made of titanium skeletons

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ABSTRACT

Purpose: The aim of the article is to present the technology of the manufacturing of composite materials with aluminum alloys matrix with reinforcement made of titanium skeletons. This paper presents the structure and properties of these composite materials.

Design/methodology/approach: Titanium skeletons manufactured by SLS technology for certain mechanical properties and geometrical features, subjected to infiltration of cast aluminium alloys: AlSi12, AlSi7Mg0.3 thereby obtain a composite materials AlSi12/Ti and AlSi7Mg0.3/Ti.

Findings: The results of examinations of mechanical properties of aluminium alloys: AlSi12, AlSi7Mg0.3, titanium skeletons and composite materials AlSi12/Ti, AlSi7Mg0.3/Ti, show that the reinforcement of aluminium alloys AlSi12, AlSi7Mg0.3 with porous titanium skeletons has a beneficial effect on the mechanical properties of the composite materials AlSi12/Ti, AlSi7Mg0.3/Ti.

Practical implications: The principal aim of modern composite materials with a reinforcement in the form of a porous metallic skeleton they are employed, among others, in the automotive, aviation, machine and space industry as well as in medicine.

Originality/value: The use of SLS technology in combination with infiltration technology creates prospects production of composite materials having improved properties and a wide range of applicability.

Keywords: AlSi12/Ti; AlSi7Mg0.3/Ti; AlSi12; AlSi7Mg0.3; Titanium skeletons; Selective Laser Sintering; Infiltration; Tensile stress; Bending stress; Compressive stress

Reference to this paper should be given in the following way:

L.A. Dobrzański, A. Dobrzańska-Danikiewicz, A. Achtelik-Franczak, The structure and properties of aluminium alloys matrix composite materials with reinforcement made of titanium skeletons, Archives of Materials Science and Engineering 80/1 (2016) 16-30.

PROPERTIES

1. Introduction

The principal aim of modern composite materials with a reinforcement in the form of a porous metallic skeleton with a high degree of porosity ranging 40-90% is to transmit loads and they are employed, among others, in the automotive, aviation, machine and space industry as well as in medicine [1-6]. A porous skeleton is fabricated in the first place during the manufacture of composite materials with reinforcement in the form of a porous skeleton [7,8], which to a high extent is dictating the properties of the future composite material; the skeleton is then undergoing specific technological processes in order to produce a composite material with improved and competitive properties in relation to the properties of the matrix material.

The demand for light and even ultra-light skeletal systems possessing a good rigidity-to-strength ratio is leading to constant efforts to reduce their mass, the result of which are extensive studies into the design and use of state-of-the-art CAD/CAM technologies in this field, in particular additive manufacturing, including also Selective Laser Sintering (SLS) and laser melting techniques [9-21]. In selective laser sintering/melting technologies, the particular phases of scanning, design and manufacturing are combined; each part is produced based on a designed three-dimensional CAD model and in its manufacturing process the particular layers of metal (in form of powder) with the designed shape are always joined by the layer-by-layer technique.

Modern designing and manufacturing tools allow to produce metallic skeletal constructions with an appropriate set of geometrical and mechanical properties which a given skeleton should posses depending on its intended use [22-24].

Composite materials are manufactured by indirect methods, of which each relates to the earlier preparation of a composite material's components of the reinforcement and matrix. Considering a given fabrication technology of composite materials, a joint is created between the reinforcement and the matrix, which can be either of the chemical character and is created in diffusion processes between the reinforcement and matrix components; of the mechanical character where the reinforcement is joined mechanically with the matrix; and of the adhesion character, created due to the occurrence of bonds between the adjoining surfaces [25].

Numerous manufacturing methods of metal-matrix composite materials are known, combining powder metallurgy methods, allowing to produce a composite material reinforcement in the form of a skeleton with open pores, with casting technologies including infiltration. The input of own works is vital in this scope [26-33].

The manufactured porous skeleton is usually ceramic [32], although it can also be metallic [34]. Then, as a result of infiltration, open pores are filled with liquid metal or metal alloy. The key aim of a porous skeleton is to locally reinforce the manufactured composite material by enhancing strength, rigidity, hardness, wear resistance and be reducing a thermal expansion coefficient. An important feature of such materials is also their relatively small density. The infiltration technology is a relatively profitable one, yielding high efficiency rates and possibilities to fabricate composite materials using various reinforcement and matrix materials [26-33,35-39].

Depending on the applied matrix material and the material selected for the matrix and the type of reinforcement, a composite material is manufactured by utilising several methods in a single manufacturing process, leading to the achievement of a final product. For instance, if aluminium alloys are used as a matrix material, depending on the reinforcement used, a combination of different manufacturing technologies is used, giving products with varied intended uses. The results of the investigations presented in this article pertain to the selective laser sintering technology for producing a porous metallic – titanium skeleton with the infiltration technology, in which the skeleton pores are filled with a matrix material – aluminium alloys as a result of the acting gas pressure above the level of the liquid matrix material.

When manufacturing technologies of skeletal porous materials applied as a reinforcement in composite materials with an aluminium alloy matrix are chosen from the available manufacturing technologies for such materials, including powder metallurgy (PM) technologies, metallic foam (MF) manufacturing technologies, casting technologies (C) and additive manufacturing (AM) technologies, procedural benchmarking techniques were applied using a dendrological matrix of technology value. In procedural benchmarking, the existing, proven procedures are implemented for another thematic area or field of knowledge. A graphical representation of procedural benchmarking is a dendrological matrix presenting the results of an analysis of preferences, being a research approach consisting of classifying objects within a specific scale as expressed by a precedence hierarchy of objects presented in an ordered manner by a preferential series. The dendrological matrix applied, being a universal and original formula, enables to transform hidden qualitative knowledge into open quantitative knowledge possible for presentation using analytical methods and tools [40-43].

The detailed assessment criteria of attractiveness and potential are adopted when choosing a porous material manufacturing technology. Taking into account the attractiveness criteria of porous materials' manufacturing technologies, a complexity level of a given technology is significant; the cost of the equipment and of the entire process as well as its environmental friendliness are also a weighty criterion of attractiveness. The ability to control geometric features and the size of the pores produced has the biggest influence on the potential of given technologies to the highest degree, and then the repeatability of geometric characteristics and the ability to produce different shapes of the materials manufactured.

An analysis of attractiveness and potential of various manufacturing technologies of porous materials is presented graphically on a dendrological matrix (Fig. 1). The attractiveness and potential coordinates for particular technologies are linking a given technology to the relevant square of the matrix to which a given characteristic is assigned. The dendrological matrix is divided into quarters – a wide-stretching oak, a soaring cypress and a rooted dwarf mountain pine and a quaking aspen, each described with a different set of characteristic features.

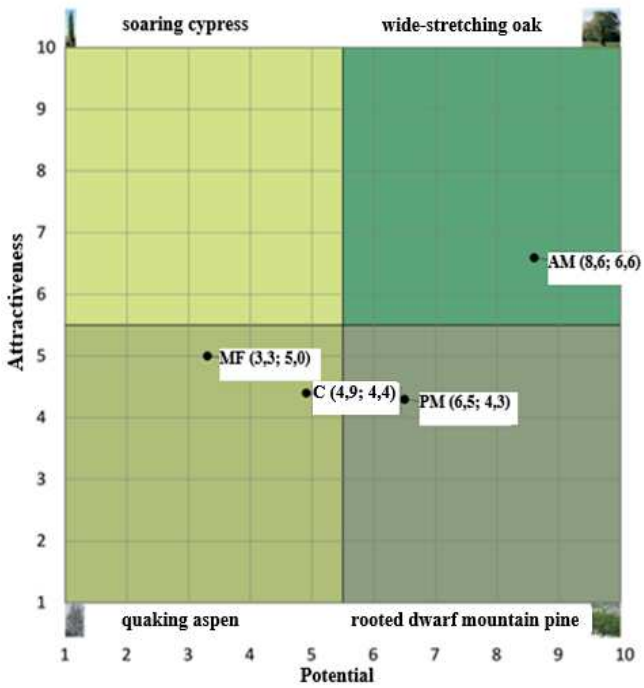


Fig. 1. The positions of specific technologies subjected to heuristic investigations using the dendrological matrix of technology value

The best set of features is in the quarter of the wide-stretching oak where the group of attractiveness and potential features is within the range of coordinates above 5.5. According to the analysis, the pool of coordinates situated in the wide-stretching oak quarter relate to additive manufacturing technologies, which proves that they exhibit the highest potential and attractiveness for the fabrication of porous materials.

The potential of additive technologies is much larger than of other technologies, and is represented chiefly by opportunities ensured by three-dimensional designing, which allows to almost fully control the materials produced in respect of their structure, dimensions and the shape of pores, and the repeatability of geometrical characteristics. The above-mentioned selective laser sintering/melting technology was chosen from the additive manufacturing technologies enabling to fabricate microporous metallic skeletons and to control their dimensions, size, shape of pores and to control the repeatability of the porous structures produced

2. The concept of aluminium alloys matrix composite materials with reinforcement made of titanium skeletons

The constructional assumptions and a technology of porous microskeletons made of titanium manufactured by Selective Laser Sintering were established principally to use, as composite elements, biologically active engineering materials or implant-scaffolds, where porous zones with appropriately sized pores are coated on the internal surfaces of pores with materials supporting the growth of living cells. This topic relates specifically to the manufacture of porous titanium skeletons with pre-defined geometric features and mechanical properties and they are not a subject of this paper, however, they represent a foundation for developing, independently, new composite materials with a cast aluminium alloys matrix and with a reinforcement made of titanium skeleton microporous materials manufactured by Selective Laser Sintering.

Hexagon cross base unit cells were selected experimentally for the titanium microskeletons, and a spatial microskeleton lattice was achieved by multiplying them with the assumed pore size of 25-450 μm and the unit cells arranged at the angle of 45° relative to the axis *y* of the system of coordinates. Microskeletons of specimens for compressive, tensile and bending tests were produced this way (Fig. 2).

Microporous titanium skeletons produced by SLS were employed to develop composite materials with predictable, broad potential applications in various fields, e.g. in the automotive, machine, aviation and electronic industry, the model of which is shown in Figure 3.

In order to produce the mentioned composites, the titanium microskeletons fabricated by SLS were subjected to pressure infiltration. The key benefits of infiltration include high profitability and the possibility to use various materials, both for the reinforcement and as the infiltrated material and a matrix as an infiltrating material. It is necessary that the infiltrating material's melting point is much higher than this of the infiltrated material, because a reinforcement is then not changing its properties under the influence of temperature. The infiltrated material are titanium microskeletons with a melting point 2.5 times higher than the melting point of the infiltrating material, for which aluminium cast alloys were chosen with the chemical composition given in Table 1.

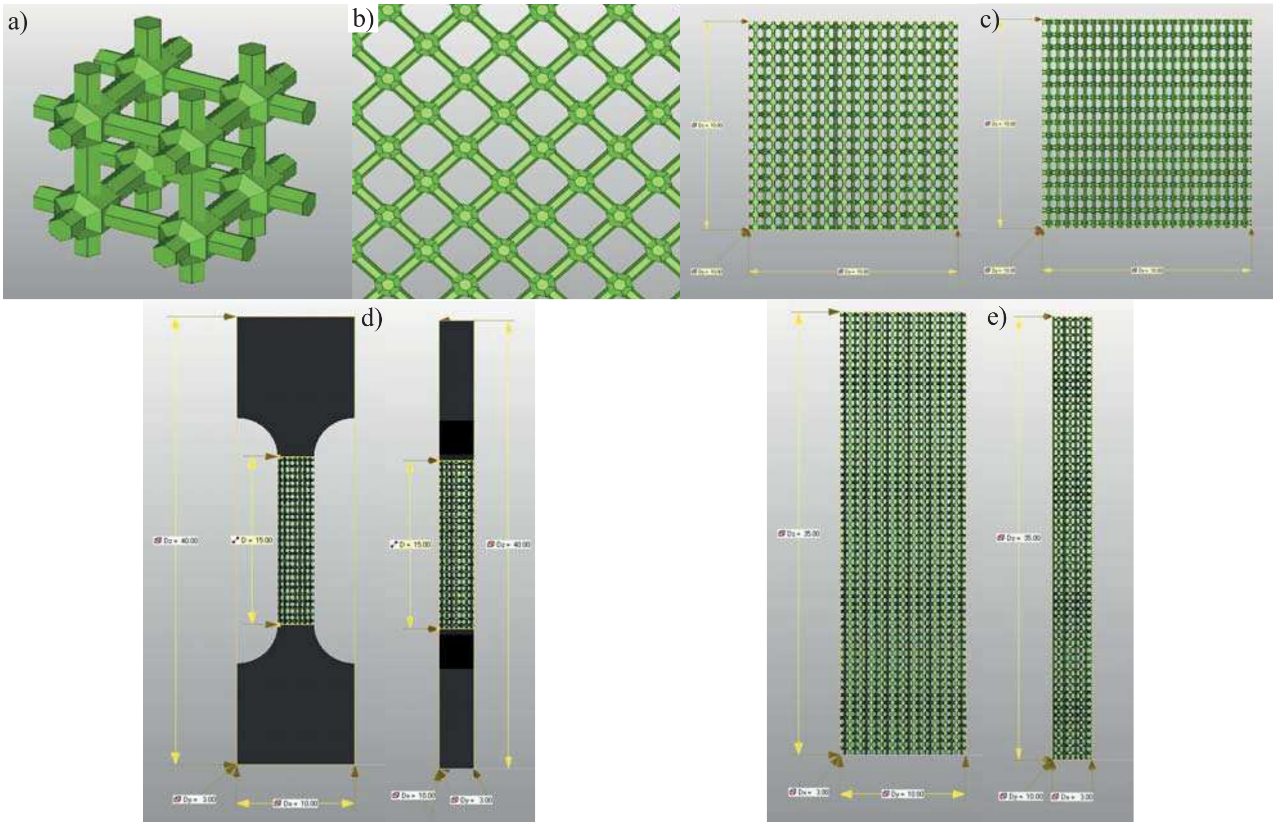


Fig. 2. The design assumptions of the spatial structure of titanium porous microskeletons manufactured by the SLS technique as the reinforcement of cast aluminium alloys matrix composite materials: a) a computer model created using a hexagon cross unit cell, b) an image of structure of a computer model presenting the arrangement of unit cells at the angle of 45° relative to the axis y of the system of coordinates, c-e) models of microskeletons of specimens for c) compressive, d) tensile and e) bending tests

Table 1.
Chemical composition of aluminium alloys being a matrix of composite materials manufactured by infiltration of titanium skeletal microporous materials manufactured by Selective Laser Sintering

Aluminium alloy symbol	Mass concentration of elements, %							
	Si	Fe	Cu	Mn	Mg	Ti	V	Al
PN-EN AlSi12	1.0-12.0	max 0.3	max 0.03	0.2-0.4	0.25-0.32	0.08-0.15	-	reszta (~88.3)
PN-EN AlSi7Mg0.3	6.5-7.5	max 0.15	max 0.05	max 0.10	0.25-0.45	0.08-0.15	max 0.03	reszta (~92.0)

Aluminium alloys were chosen because they are relatively widespread in production of composite materials. Aluminium alloys have low density, of 2.7 g/cm^3 for aluminium, which is beneficial for the so-called specific strength, i.e. a ratio of tensile strength and density. The alloys are also characterised by good corrosion resistance, resistance to sea water, and also resistance to different other chemical mediums such as ammonia and nitric acid. The mentioned aluminium alloys have also good mechanical properties which may increase as a concentration of Mg is changing, and for this reason, for comparative purposes, two aluminium alloys with Mg added and not added, were chosen. The mentioned aluminium alloys were chosen from a number of aluminium alloys due to their technological properties, which may facilitate infiltration by penetrating titanium microskeletons, such as:

- relatively high castability;
- good and accurate filling of pores;
- small cast shrinkage;
- low susceptibility to hot cracking.

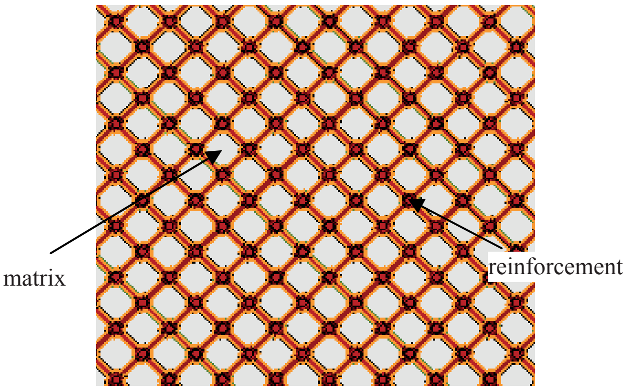


Fig. 3. The chart of the structure of cast aluminium alloy composite materials and reinforcement made of titanium porous microskeletons manufactured by Selective Laser Sintering

The titanium microskeletons were subjected to infiltration with AlSi12 and AlSi7Mg0.3 alloys in the liquid state with the temperature of 800°C for 2 min. under the pressure of 2-3 MPa of the gas situated above the liquid matrix material, and composites with a new set of properties were achieved. Infiltration takes place in autoclave (Fig. 4), to which inert gas is fed under the pressure of several MPa. Porous preforms in the form of titanium microskeletons are fixed to the autoclave cover, and are submerged in the melted alloy after closing the cover. The liquid aluminium alloys – under the influence of the pressure of the supplied inert gas – are pressed into the pores of microskeletons, until they are filled completely. The matrix material is crystallising following the infiltration, thus forming a composite material with the skeleton.

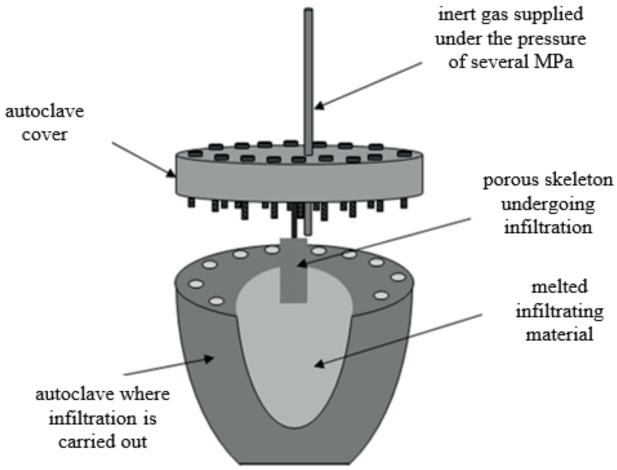


Fig. 4. Scheme of the instrument where infiltration is performed

For the purpose of comparing the structure and properties of a new class of AlSi12/Ti and AlSi7Mg0.3/Ti composite materials produced by pressure infiltration with the matrix of cast aluminium alloy PN-EN AlSi12 and PN-EN AlSi7Mg0.3 and with a reinforcement in the form of titanium porous microskeletons manufactured by Selective Laser Sintering, solid titanium was also fabricated using the SLS technique, having the same sizes and geometric features as given in Figure 2. The selectively laser sintered solid titanium was produced by selecting the laser power of 60 and 100 W with different laser beam diameters of 50, 70 and 90 µm, and then power was increased up to 110 W for the chosen laser beam diameter and by using the distance values between laser beam and laser remelting paths as being equal to the laser beam diameter.

3. The results of investigations into the structure of aluminium alloys matrix composite materials with reinforcement made of titanium skeletons

The density of solid titanium produced by Selective Laser Sintering is dependent upon the laser power of 60-110 W. The density, corresponding to the density of solid titanium of 4.51 g/cm^3, obtained by traditional manufacturing methods, e.g. by casting, can only be achieved after

SLS with the power of 110 W. The solid titanium structure, more compacted and more densified, having a marked laser path (Fig. 5), depends on the use of higher power of laser of 100 and 110 W and a smaller laser beam diameter of 50 µm, as opposite to solid titanium manufactured with the laser power of 60 W (Figs. 4a-c), which is inhomogeneous, with void spaces and with no laser path being marked. The width of the laser path on the solid titanium surface should correspond to the laser beam diameter used for the fabrication of solid titanium.

The X-ray qualitative phase analysis method has confirmed the presence - in solid titanium achieved by SLS – of a crystalline Tiα phase without the presence of any oxides or other phases (Fig. 6). This is also confirmed by analysing scattered X-ray radiation energy (EDS) in a scanning electron microscope (Fig. 6).

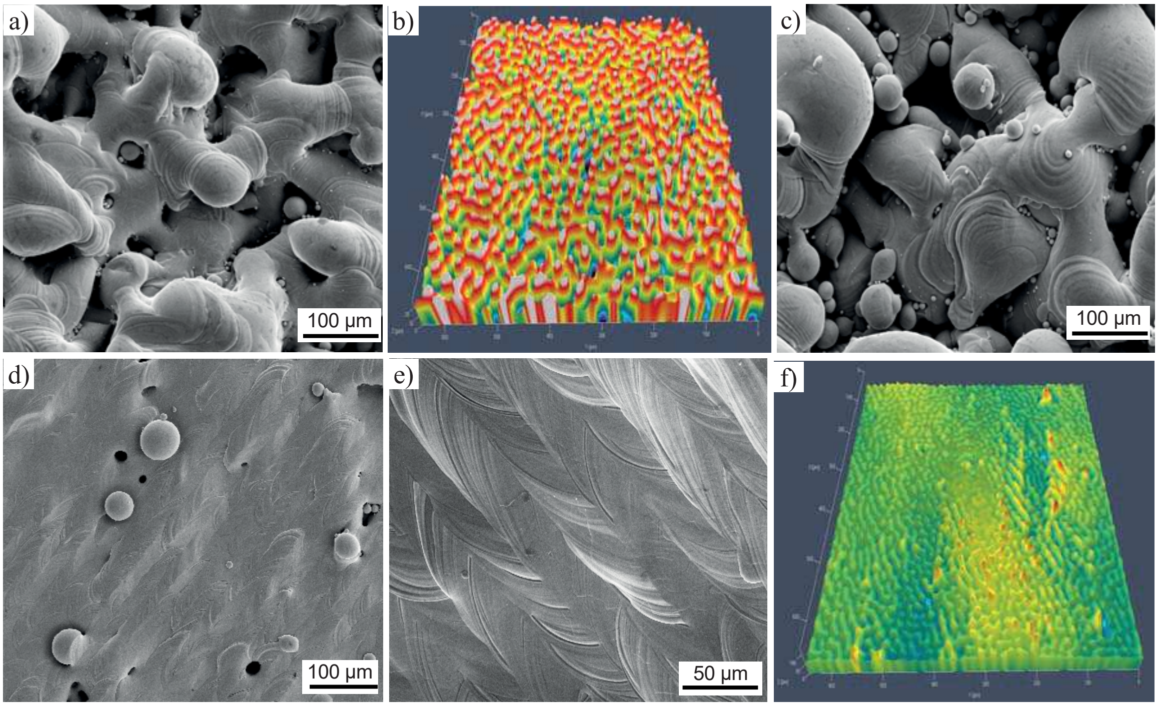


Fig. 5. The surface topography of selectively laser sintered solid titanium: a,b) with the laser power of 60 W with the laser beam diameter of 50 µm, c) with the laser power of 60 W with the laser beam diameter of 90 µm, d) with the laser power of 100 W with the laser beam diameter of 50 µm, e,f) with the laser power of 110 W with the laser beam diameter of 50 µm; a,c-e) SEM, b,f) confocal microscope

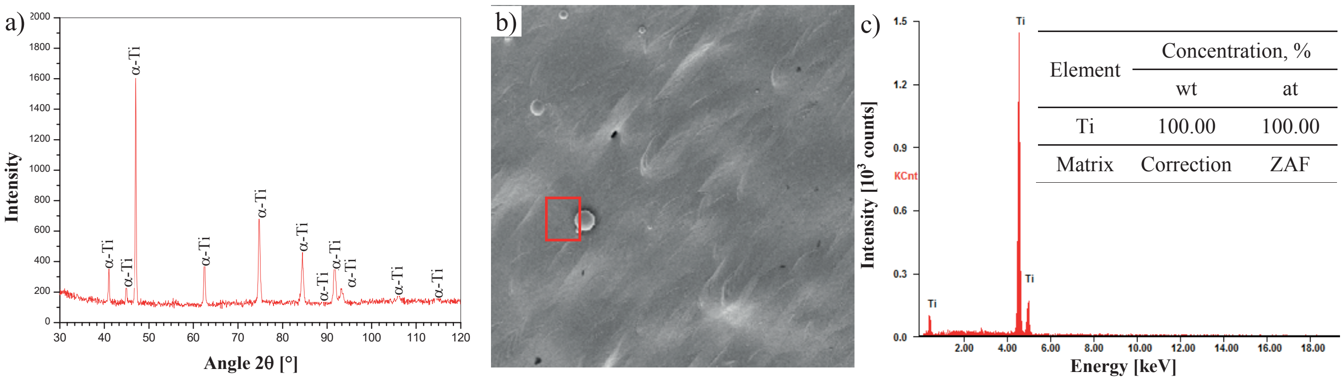


Fig. 6. a) X-ray diffraction pattern of solid titanium, b) surface topography of selectively laser sintered solid titanium fabricated with laser power of 110 W, c) chart of scattered X-ray radiation and result of quantitative analysis of chemical composition from the area marked in Figure b

By means of the X-ray diffraction method, the presence of Al, Tiα phases and AlSiTi phase in the form of aluminium-titanium silicide $Al_{0.57}Si_{1.5}Ti_{0.93}$ was confirmed in the structure of pressure-infiltrated AlSi12/Ti and AlSi7Mg0.3/Ti composites with the cast aluminium alloys matrix and with reinforcement made of titanium skeleton microporous materials manufactured by Selective Laser Sintering, the presence of which was identified according to a sheet with reference code 98-060-9348. The presence of this phase was also confirmed on the chart of scattered X-ray radiation energy (EDS) of composite materials, both, AlSi12/Ti and AlSi7Mg0.3/Ti (Fig. 8).

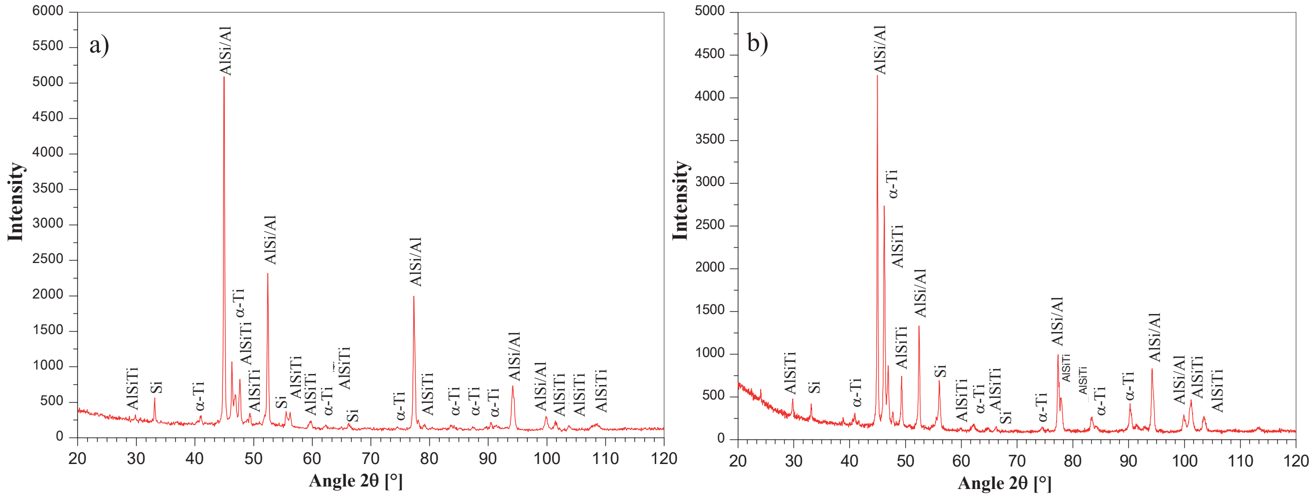
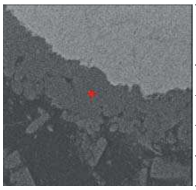
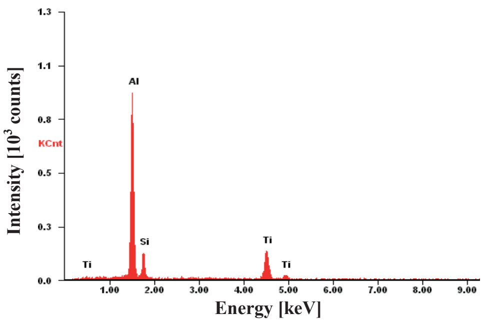
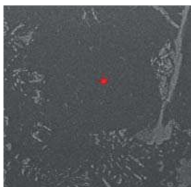


Fig. 7. X-ray diffraction patterns of composite materials a) AlSi12/Ti, b) AlSi7Mg0.3/Ti



Element	Concentration, %	
	wt	at
Al	54.19	64.63
Si	09.68	11.09
Ti	36.13	24.27
Matrix	Correction	ZAF





Element	Concentration, %	
	wt	at
Al	100.00	100.00
Matrix	Correction	ZAF

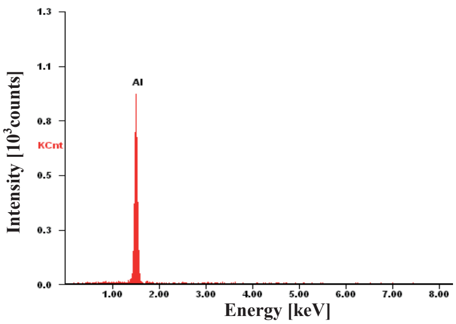


Fig. 8. Structure of AlSi7Mg0.3/Ti composite material (microsection, SEM) and charts of scattered X-ray radiation and results of quantitative chemical composition analysis of AlSi7Mg0.3/Ti composite material from the marked location

The structure of AlSi12/Ti and AlSi7Mg0.3/Ti composites (Fig. 9) confirms that the pores of the titanium microskeleton are filled thoroughly with the matrix material as a result of infiltration, without any voids in the matrix-and-reinforcement bonding zones, and the titanium microskeleton retains its shape and structure, which can be exactly separated in the composite material structure. The dark areas visible on the metallographic microsections show a titanium microskeleton, and lighter points correspond to the matrix AlSi12 or AlSi7Mg0.3. The contrast in a scanning electron microscope is reverse, because lighter points correspond to the titanium microskeleton, as the matrix material is shown as darkest. An interphase is presented indirectly, formed between titanium and the matrix material. In a confocal laser microscope, the matrix material can be differentiated from the titanium skeleton based on the difference of levels. Figure 10 shows the surface distribution of elements in pressure-infiltrated AlSi12/Ti and AlSi7Mg0.3/Ti composites of composite materials with the cast aluminium alloys matrix and with reinforcement made of titanium skeleton microporous materials manufactured by Selective Laser Sintering.

4. The mechanical properties of aluminium alloys matrix composite materials with reinforcement made of titanium skeletons

Strength properties were examined for solid titanium specimens with varied density and also for the newly developed pressure-infiltrated AlSi12/Ti and AlSi7Mg0.3/Ti composite materials using titanium microskeletons with varied porosity, fabricated by SLS.

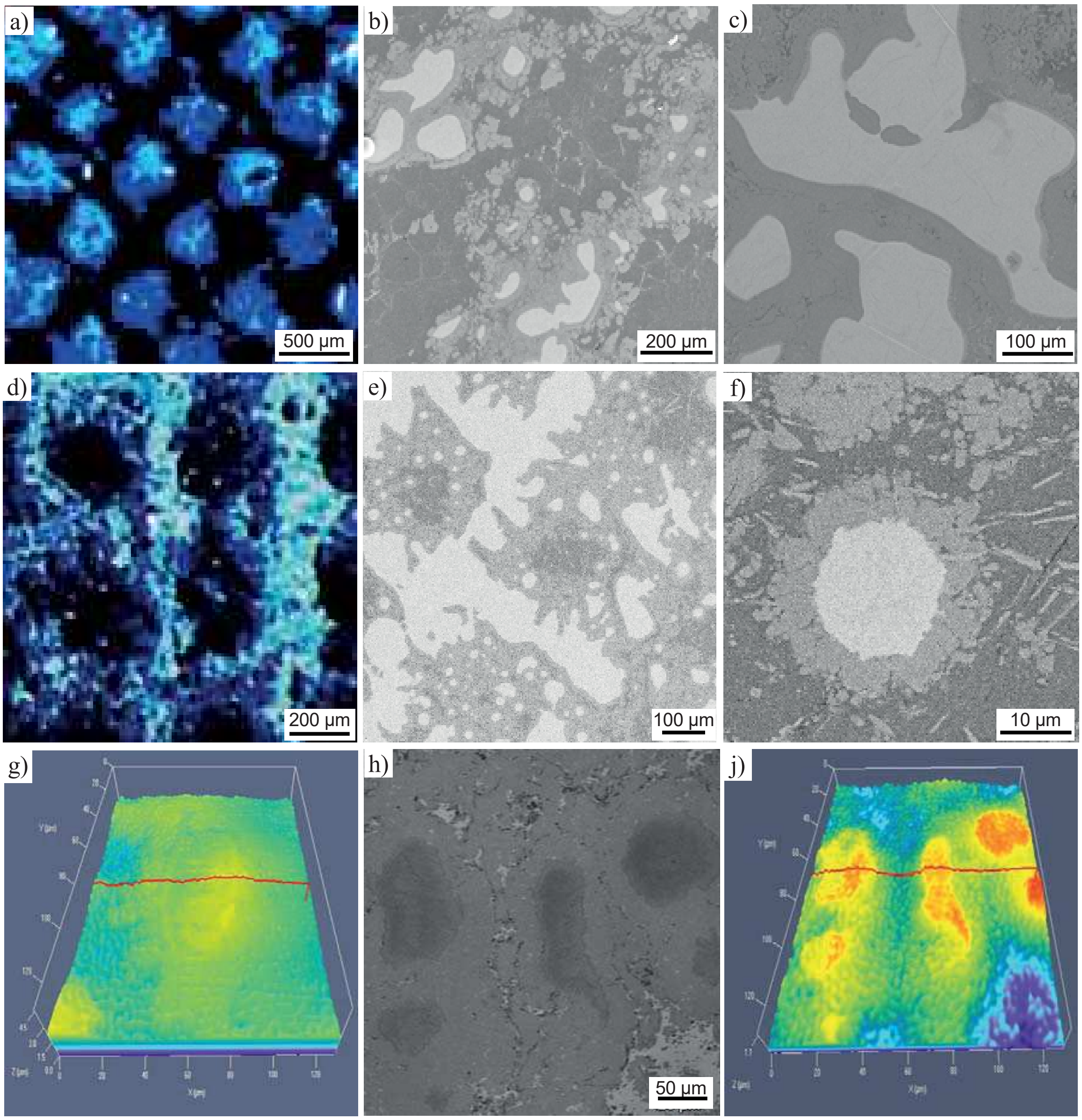


Fig. 9. Structure of the following composite materials: a,b,c,g) AlSi12/Ti, d,e,f,h,j) AlSi7Mg0,3/Ti, a,d) microscope, b,c,e,f) SEM, g,h,j) confocal microscope

Consequently, the examinations were performed using miniaturised specimens (Fig. 11) and as assumed previously for examination of titanium skeleton microporous materials manufactured by Selective Laser Sintering. Static tensile tests, three-point bending tests and compression tests were performed with a universal tensile testing machine Zwick. Each of the specimens used for testing mechanical properties was made individually as per the established assumptions. 5 specimens were made for each series of tests.

Tensile strength tests were carried out using specimens with the quadrangular section of 3x3 mm and measuring length of 15 mm. A static three-point bending test was made with a flat specimen with the dimensions of 35x10x3 mm with the distance of 30 mm between supports. Bending strength tests were carried out for specimens dimensioned 10x10x10 mm. The dependency chart of, respectively, tensile force or compressive force or bending moment in the function of elongation, deformation or specimen deflection value, was registered continuously during strength measurements.

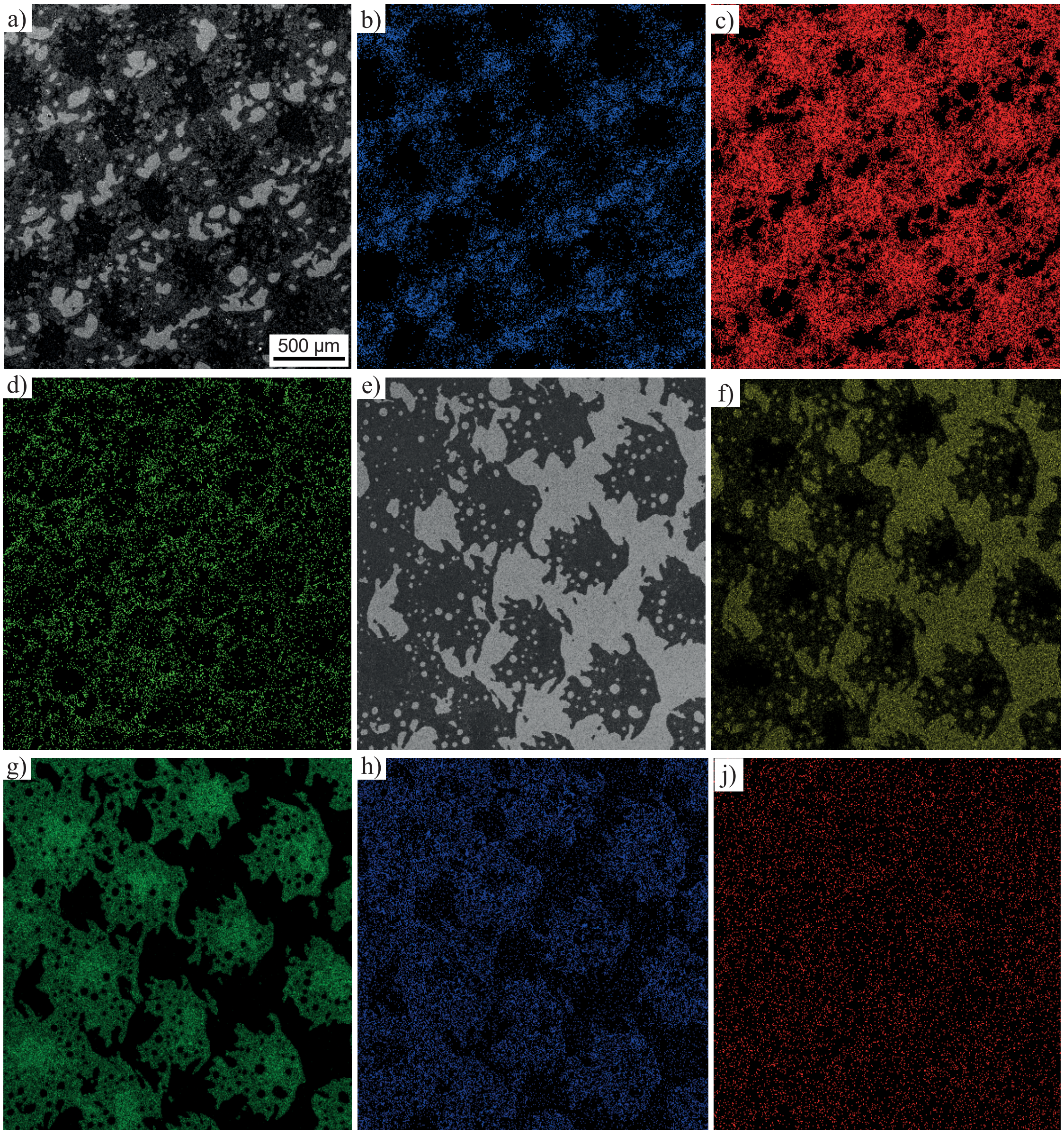


Fig. 10. Structure of the surface layer of composite material: a-d) AlSi12/Ti, e-j) AlSi7Mg0,3/Ti; a,e) SEM image; surface distribution of elements: b,f) Ti, c,g) Al, d,h) Si, j) Mg

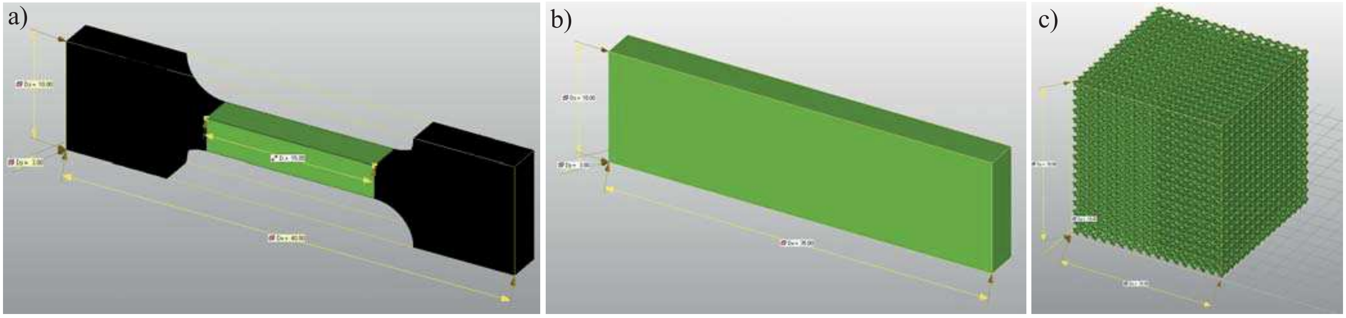


Fig. 11. Computer model image of specimens for static test: a) tensile test, b) three-point bending test, c) compression test

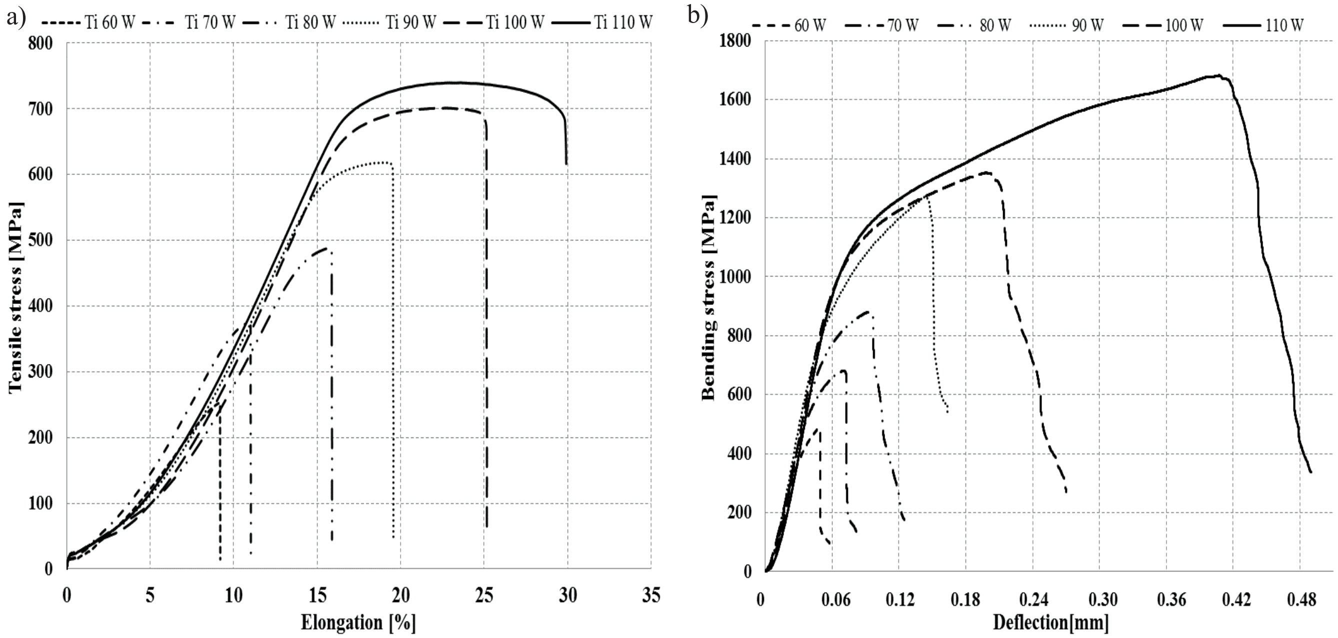


Fig. 12. Stress dependencies chart: a) dependency between tensile stress and elongation, b) dependency between bending stress and deflection value for solid titanium specimens fabricated by SLS using the different laser power of 60 to 110 W

When solid titanium is produced by the method of Selective Laser Sintering, as the laser power is rising so is rising its density, leading to increased tensile strength (Fig. 12) by about 3 times from 252.4 MPa with the laser power of 60 W to 743.9 MPa for the maximum laser power applied of 110 W; moreover, tensile strength is also increased by about 3.5 times from, respectively, 486.7 MPa to 1681.9 MPa and the Young's longitudinal elongation elasticity modulus is rising from 30.93 GPa to 102.85 GPa. The solid titanium produced by SLS with a higher laser power of 110 W is characterised in a tensile test by about 20% higher elongation, and by a substantial deflection value of 0.40 mm in a bending test. Stronger and more plastic solid titanium is achieved by using a higher laser power.

AlSi12/Ti and AlSi7Mg0.3/Ti composite materials infiltrated using two types of titanium microskeletons with the pore size of ~350 and ~250 μm and the porosity of, respectively, ~66 and ~56% and the bending strength of, respectively, 65 and 100 MPa, underwent tensile strength tests and were compared to the strength of AlSi12 and AlSi7Mg0.3 aluminium alloys and solid titanium produced by SLS. The bending strength of the solid titanium of 1682 MPa is nearly ten times higher than for AlSi12/Ti alloy (Fig. 13), but only more than four times higher than for the AlSi12/Ti composite material. The reinforcement of aluminium alloys with porous titanium skeletons has a beneficial effect also on the mechanical properties of the composite materials developed. AlSi12 alloy is

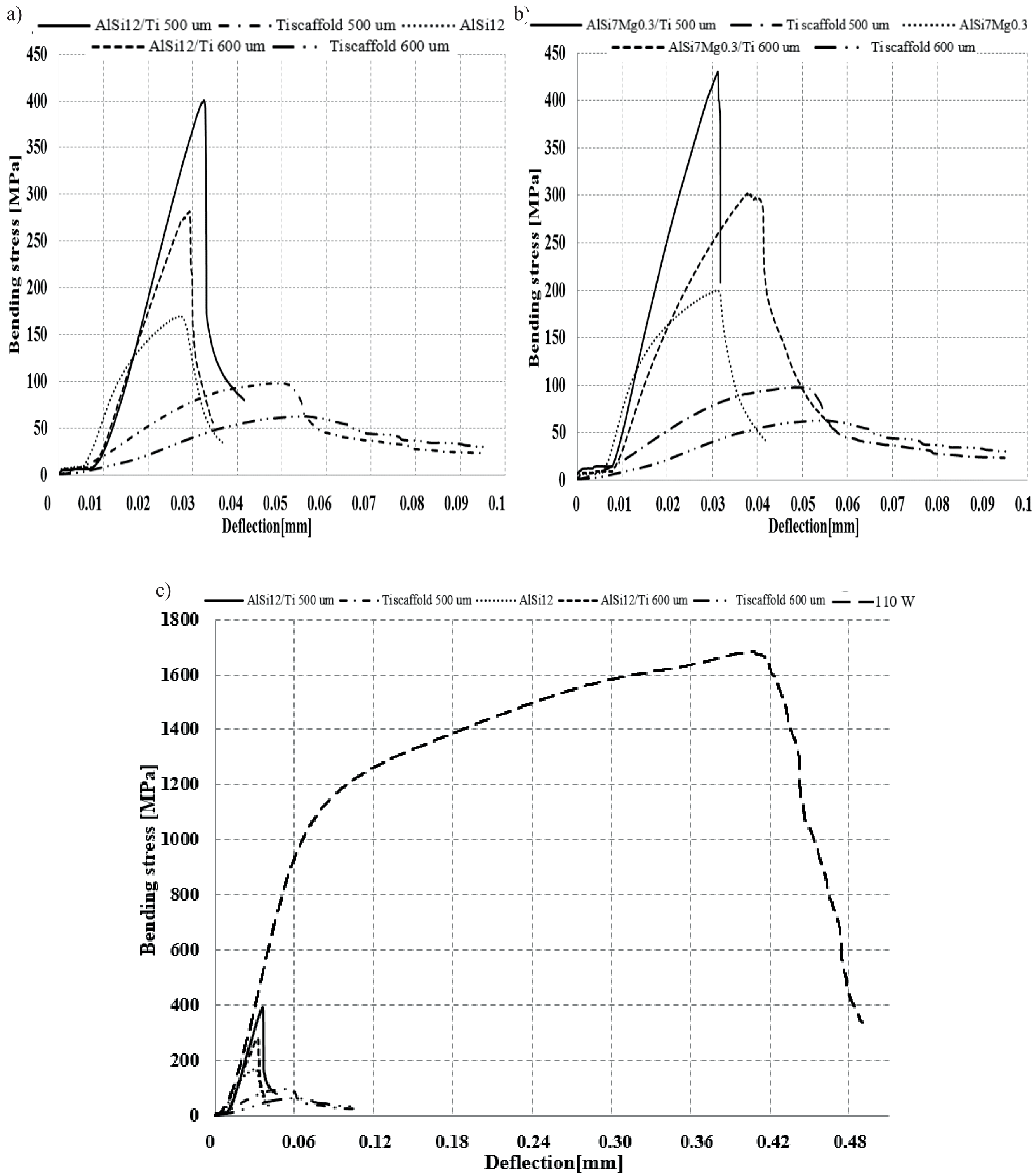


Fig. 13. Bending stress-to-deflection value dependency chart for: a) AlSi12/Ti composite material, AlSi12 alloy, titanium porous microskeleton; b) AlSi7Mg0.3/Ti composite material, AlSi7Mg0.3 alloy, titanium porous microskeleton; c) solid titanium, titanium microskeleton, AlSi12 alloy, AlSi12/Ti composite material

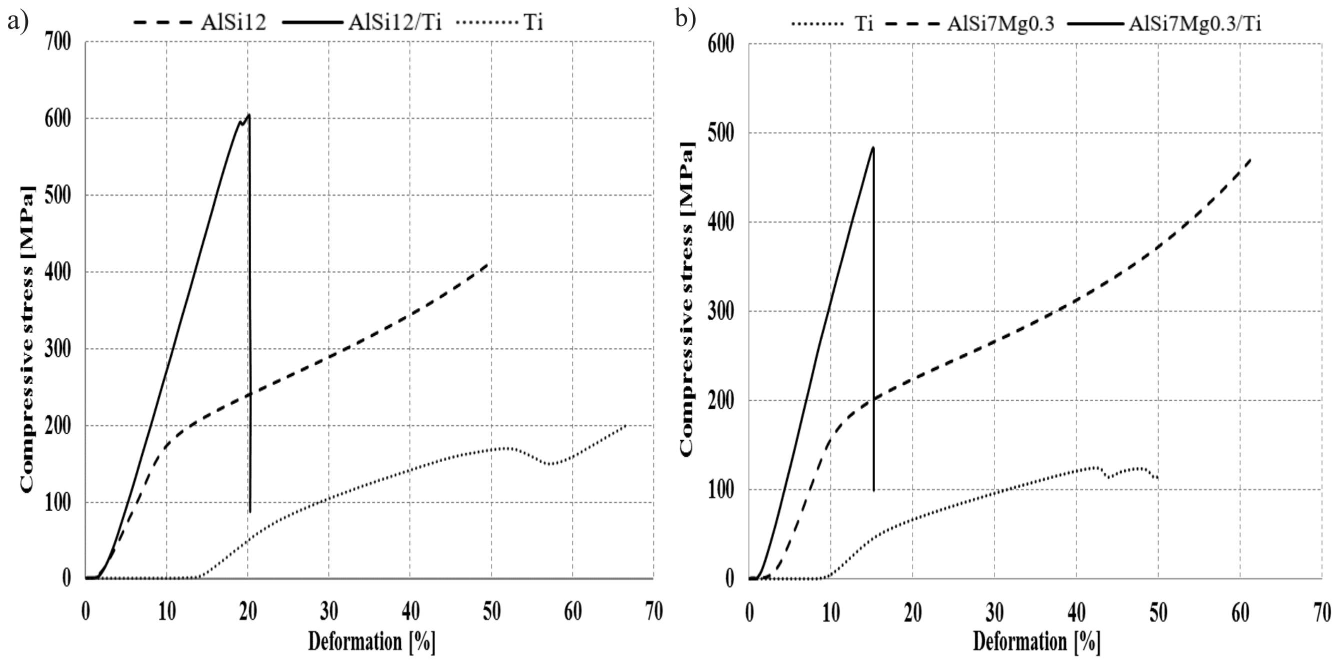


Fig. 14. Bending stress-to-deflection value dependency chart for: a) AlSi12/Ti composite material, AlSi12 alloy, titanium porous microskeleton; b) AlSi7Mg0.3/Ti composite material, AlSi7Mg0.3 alloy, titanium porous microskeleton

characterised by bending strength of about 170 MPa, and in case of a composite material made with a titanium microskeleton with the porosity of, respectively, 56 and 66%, bending strength is rising to ~400 and ~280 MPa (Fig. 13).

The bending strength of AlSi12/Ti composite material with a titanium microskeleton with higher porosity of 66% is increased by ~110 MPa, whereas when porosity is smaller by 56%, strength is increased by ~230 MPa as compared to the matrix material. The bending strength of AlSi7Mg0.3 aluminium alloy is ~200 MPa, and reaches – for AlSi7Mg0.3/Ti composite materials – respectively, ~300 and ~430 MPa, which increases strength by ~100 and ~130 MPa as compared to the matrix material. The higher bending strength is corresponding to the smaller porosity of a titanium microskeleton, because the reinforcement of composite materials has a dominant effect on strength when the same matrix material is used, and when different matrix materials are used, but microskeletons with the same porosity, the strength of the matrix is decisive mainly for the strength of the composite material.

The maximum stress, when compressing AlSi12/Ti composite material (Fig. 14), reaches ~600 MPa, and then its dramatic fall is seen. In the case of maximum compressive strength, the specimen is destroyed, and cracks at the angle of 45° occur at the side surface of the specimen (Fig. 15). The AlSi7Mg0.3/Ti composite material behaves in a similar way, and its compressive strength reaches the value of about 470 MPa. The higher the strength of a porous microskeleton, the more resistant to compression is the composite material. Figure 15 shows the fractures of AlSi12/Ti and AlSi7Mg0.3/Ti composite materials and AlSi12 and AlSi7Mg0.3 aluminium alloys for bending and compression tests.

5. Conclusions

The newly developed microskeleton composite materials manufactured by the method of pressure infiltration with selected cast aluminium alloys, i.e. AlSi12 or AlSi7Mg0.3, of microporous titanium skeletons produced by selective laser sintering, create an opportunity to fabricate parts with relatively small sizes and requiring no further finishing in order to achieve the final shape and geometric form, which are dedicated, in particular, to the automotive, machine and aviation sector.

It is signified by investigations into the feasible uses of titanium microskeletons for the fabrication of composite materials by way of infiltration, that their use as a reinforcement in composite materials has a significant effect on the structure change because multi-component phases are created between the reinforcement material and the matrix material and by improving mechanical properties of such a material.

The results of examinations of mechanical properties of composite materials with the AlSi12 and AlSi7Mg0.3 matrix reinforced with titanium microskeletons manufactured by selective laser sintering show that, during tensile and bending tests, the progression of curves of, respectively, tension and bending of composite materials, is analogous to the progression of the relevant curves for aluminium alloys, with such a difference that specimen destruction for composite materials takes place at a much higher stress.

It was found by analysing the progression of the compression curve that the investigated materials, both, the composite materials and aluminium alloys, have a different progression of compression curves, which is connected with different properties of such materials. A compression curve of aluminium alloys corresponds to elastic-plastic materials, whereas the progression character of the compression curve for composite materials is definitely determining such materials as materials with brittle properties.

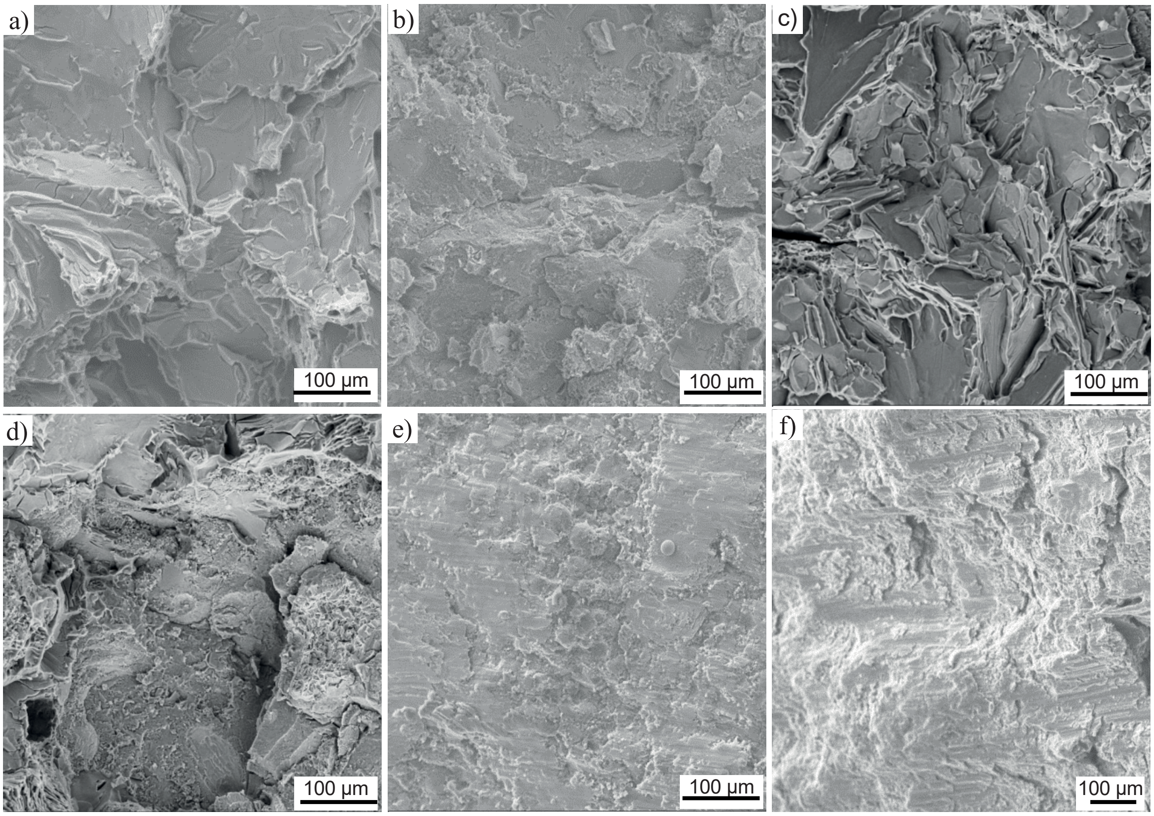


Fig. 15. Structure of fracture after: a-d) bending test, a) AlSi12 alloy, b) composite material with reinforcement made of titanium microskeleton and matrix as AlSi12 alloy, c) AlSi7Mg0.3 alloy, d) composite material with reinforcement made of titanium microskeleton and matrix as AlSi7Mg0.3 alloy; e,f) after compression test of composite material: e) AlSi12/Ti, f) AlSi7Mg0.3/Ti

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