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Bimetal Castings with a Titanium Working Layer

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Abstract

The paper presents the technology of bimetallic castings using the casting method of applying layers directly during the casting process. The bimetallic casting consists of a load-bearing part (typical casting material, i.e. gray cast iron with flake graphite) and a working part (titanium insert). The titanium insert was made by printing using the selective laser melting (SLM) method, and its shape was spatial. The verification of the bimetallic castings was carried out mainly based on metallographic tests, temperature and thickness measurements. Structure examinations containing metallographic microscopic studies with the use of a light microscope (LOM) and a scanning electron microscope (SEM) with microanalysis of the chemical composition (energy dispersive spectroscopy - EDS).The aim of the tests was to select the appropriate geometrical insert parameters for bimetallic castings within the tested range. The correct parameters of both the insert, pouring temperature and the casting modulus affect the diffusion processes and, consequently, the formation of carbides and the creation of bimetallic castings.

Keywords: Bimetallic casting, Insert, 3D printing

1. Introduction

Titanium (Ti) and its alloys feature a unique combination of high strength, good corrosion resistance, adaptability over a wide temperature range, excellent ductility and low density [1-3] For this reason, titanium (Ti) and its alloys have become well-known materials for various technological and industrial applications in the biomedical, transportation (aerospace), chemical and automotive sectors [4-6].

On the other hand, carbides, and above all titanium carbide (TiC), are among the hardest metal carbides with a Vickers hardness ranging from 28 to 35 GPa and 9–9.5 in the Mohs scale. Titanium carbide (TiC) according to Ulman belongs to the group of metal-like carbides [7], it crystallizes in the B1 type structure (Fig. 1). Carbon is incorporated into the titanium structure in the octahedral voids. In addition, the carbide has a very high melting point of 3067°C with 44% atomic carbon content (Fig. 2). TiC combines the features of metal and ceramics, shows high thermal and electrical conductivity at a level comparable to titanium, and has a low coefficient of friction. The material is resistant to water, acids, bases and the solutions of organic compounds. It maintains physical and chemical stability at ambient and high temperatures [8-10].

The properties of titanium carbide allows us to use it in composites of metal matrix composites (MMC), ceramic matrix composites and cermets. Thanks to its high refractoriness, they are used in special refractory materials. High hardness allows us to use TiC to make cutting tools [8, 11].

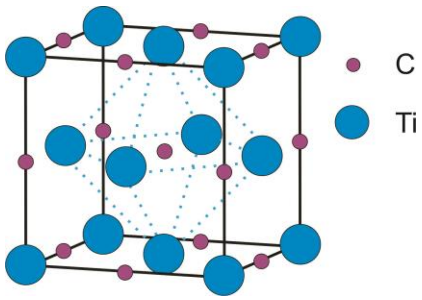


Fig. 1 TiC crystal structure [11]

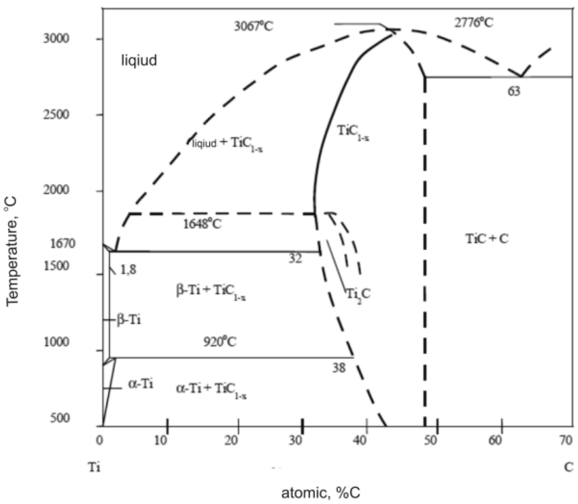


Fig. 2. Ti-C phase diagram [8]

Metal matrix composites (MMC) are materials whose matrix is made of metal, while metal carbides, ceramics and metals are most often used as reinforcement. The aim of combining the matrix and reinforcement materials is to obtain the properties of the composite corresponding to the characteristics of both phases. The reinforcing phase comes in many shapes and sizes. Composites are reinforced with dispersion particles, flakes, short fibers, whiskers and continuous fibers. There are also layered composites. The most commonly used methods for producing metal matrix composites (MMC) are metal casting methods and powder metallurgy. The most commonly used casting method for the production of a metal matrix composite is the pressurized infiltration of porous inserts made of ceramic fibers with a light metal alloy [8].

The currently used matrix materials include most often light metals, such as magnesium alloys, aluminum alloys and titanium alloys, as well as high-temperature nickel-based superalloys. Metal carbides, metal nitrides, metal borides and metal oxides are used as the alloys' reinforcing phase. Composites based on the matrix of titanium alloys are reinforced mainly with titanium borides (TiB) and titanium carbides (TiC) [12].

Titanium is also used to produce composites with the additive method – high complexity structures at a maximum material efficiency, low tool and labor costs and low environmental impact. This method allows us to produce complex components with a good surface finish with no need to use complex processes.

One of the applications of the above-mentioned method is forming complex lattice structures. Lattice structures feature high strength, stiffness, better energy absorption, excellent thermal and acoustic properties and a very good strength to weight ratio. The majority of structures are built using the laser powder bed fusion (L-PBF) method. An example lattice structure is shown in Fig. 3 [13].

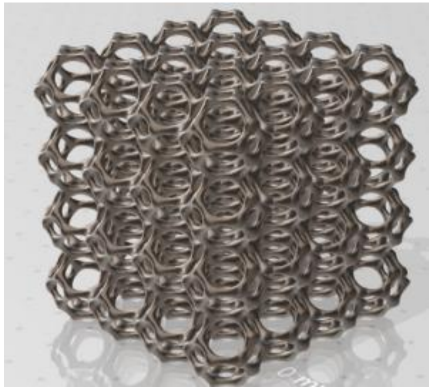


Fig. 3. Tetrakaidecahedron lattice developed with Netfabb Lattice Commander [13]

One of the most economical methods of reinforcing casting surface layers resulting primarily in increasing abrasion resistance and its strength is the casting process. The casting method of producing bimetals castings consists in the appropriate preparation of the mold by placing the insert (or applying a layer) in the area where higher properties are desired. The process of bimetal castings depends on many physical and chemical factors. The layer is formed as a result of interaction between liquid metal poured into the mold with a coating – insert (monolithic, granular or skeletal). The properties obtained depend mainly on the cooling conditions and on the reaction on the metal/insert surface, i.e. on the type of insert material effect on the casting, in the conditions of pouring and cooling of the casting.

Equally important is also the selection of alloy for casting applications, which often requires reaching a compromise between mutually exclusive material properties. Applications that require both high ductility and high hardness often lead to significant compromises, as high hardness is beneficial for wear resistance, but at the same time results in low ductility. Materials to be used in highly abrasive environments have to be not only abrasion-resistant, but also need to show adequate strength to withstand breakage and destruction [14]. Therefore, it is very advantageous to be able to combine two materials showing different qualities. Numerous research projects [15-17] conducted in the field of metal casting have shown that the two alloys can be fused in the casting process to form a bimetallic castings showing a strong, seamless metallurgical bond. The production of such bimetallic castings is a unique way of obtaining castings with good surface properties, if the internal properties of the casting are irrelevant.

The main purpose of the production of bimetallic castings is primarily to increase the functional properties of only the working

part of the casting, while the remaining part serves only as a load-bearing structure, not exposed to factors caused by, for example, abrasive wear or corrosion [14].
The aim of the research was to obtain bimetallic castings using 3D printing to prepare a spatial insert. The main purpose of the research was to select the appropriate geometrical insert parameters for bimetallic castings within the tested range. In the research attempts were made to select the appropriate geometrical parameters of the titanium insert in order to obtain a permanent bond.

2. Materials and Methods

As part of the research project bimetallic castings were made. They consist of two basic components, i.e. a load-bearing part and a working part (layer). The load-bearing part of the layered casting consisted of typical casting material, i.e. grey cast iron with flake graphite in pearlitic matrix, while the working part comprised a titanium. The insert is a spatial structure made by using the 3D printing method in the selective laser melting (SLM) process. The insert was printed using pure powdered titanium with a granularity of up to 50 μm. The shape of inserts is cuboid with dimensions 80x24x24 mm (Fig. 4). The insert has a spatial structure in the form of interconnected links with a circular cross-section (external diameter 3 mm), arranged horizontally and vertically in the shape of a lattice. The inner diameter of links (R_w) is respectively: 2.25 mm or 1.5 mm or 0 mm (full), as shown in Fig. 5. Inserts of this type have been placed in the silica sand with bentonite sandmix mould cavities with no preheating.

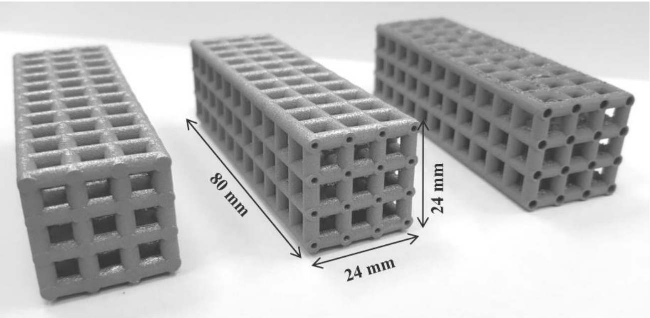


Fig. 4. Actual view of titanium inserts printed by using the selective laser melting (SLM) method

In order to make test bimetallic castings with dimensions 160x70x100, 120x70x100 and 80x70x100 mm, a insert was placed in sand molds (Fig. 6), subsequently filled with liquid gray cast iron at a temperature of 1450°C.

a)

b)

c)

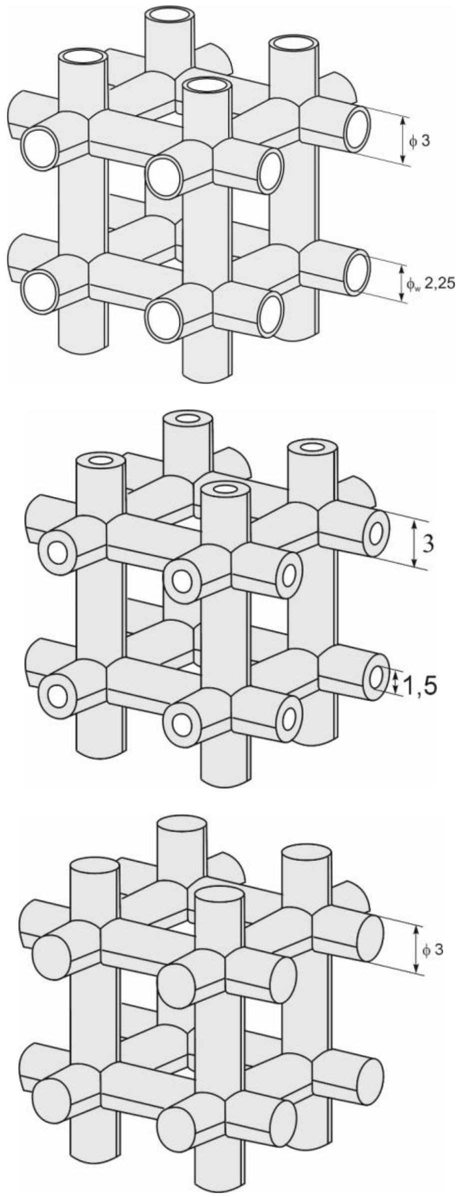


Fig. 5. The shape of 3D printed titanium insert, where the inner link diameter (R_w) is: a) 2.25 mm, b) 1.5 mm, c) 0 mm

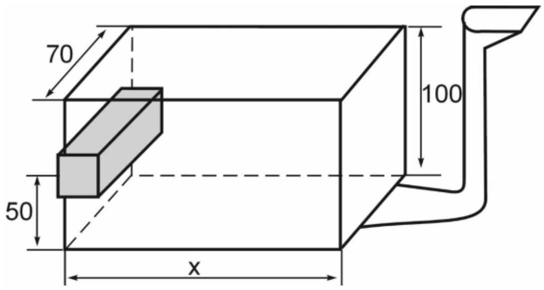


Fig. 6. Schematic diagram for the casting – insert arrangement; X = 160; 120; 80 mm

The pouring temperature was measured using the PZ20 Keller HCW pyrometer while the temperature at the insert – mold interface was measured with the Pt-PtRh10 thermocouple using an analog-digital converter (the measurement location is shown in Fig. 7).
Microscopic metallographic tests were performed using both a light microscope Nikon Eclipse LV150I and the Phenon ProX scanning electron microscope (SEM) equipped with an X-ray energy dispersion spectrometer.
The thickness of the "layer" was also measured on the scale of one link. The measurement was taken on the cross-section of the casting using a light microscope.

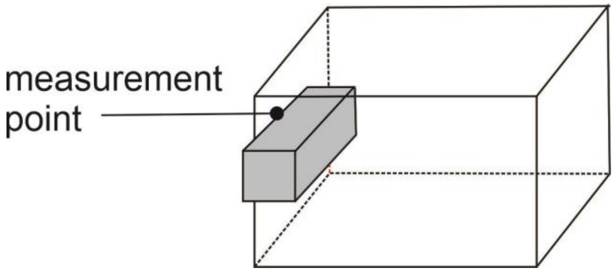


Fig. 7. Temperature measurement site

3. Results

Temperature measurement
Table 1 presents temperatures recorded both on the stream and at the insert-mold interface. The site for temperature selection in the mold was chosen to define the minimum temperature needed to permanently connect the bimetal components. The measurements taken showed that the average temperature needed to activate the insert-cast iron reaction is about 1144 ^{o}C, within the tested experimental scope. It should be emphasized that this temperature is not the lowest temperature needed for the reaction necessary to permanently connect the two materials – in the tested range it was 1119^{o}C.

Table 1.
Temperature measurements

Casting No.	Casting size, mm	inner diameter of link (R_w), mm	Pouring temp., ^{o}C	Maximum temp. at interface insert – mold, ^{o}C
W-160-2.25	160x70x100	2.25	1132	1316
W-160-0	160x70x100	0	1126	1280
W-160-1.5	160x70x100	1.5	1126	1367
W-120-2.25	120x70x100	2.25	NM	1270
W-120-0	120x70x100	0	1194	1293
W-120-1.5	120x70x100	1.5	1135	1340
W-80-2.25	80x70x100	2.25	1151	1342
W-80-0	80x70x100	1.5	1119	1276
W-80-1.5	80x70x100	0	1221	1312

NM - no measurement

Microstructural studies
To specify the impact of casting module (casting size) and the type of insert (inner diameter of the insert link) microscopic studies were carried out.
Figures 8-10 present the microstructures of titanium insert connection zone that makes the working layer of bimetal casting with cast iron load-bearing part. The microstructure of the connection zone in such layered bimetal castings is primarily affected by the carbon diffusion phenomena from the load-bearing part to the working part as well as heating the insert to high temperature resulting from the liquid metal (cast iron) poured into the mold. As a result of these phenomena, a microstructure consisting of numerous titanium carbide precipitates is formed in the area of the connection of both materials.

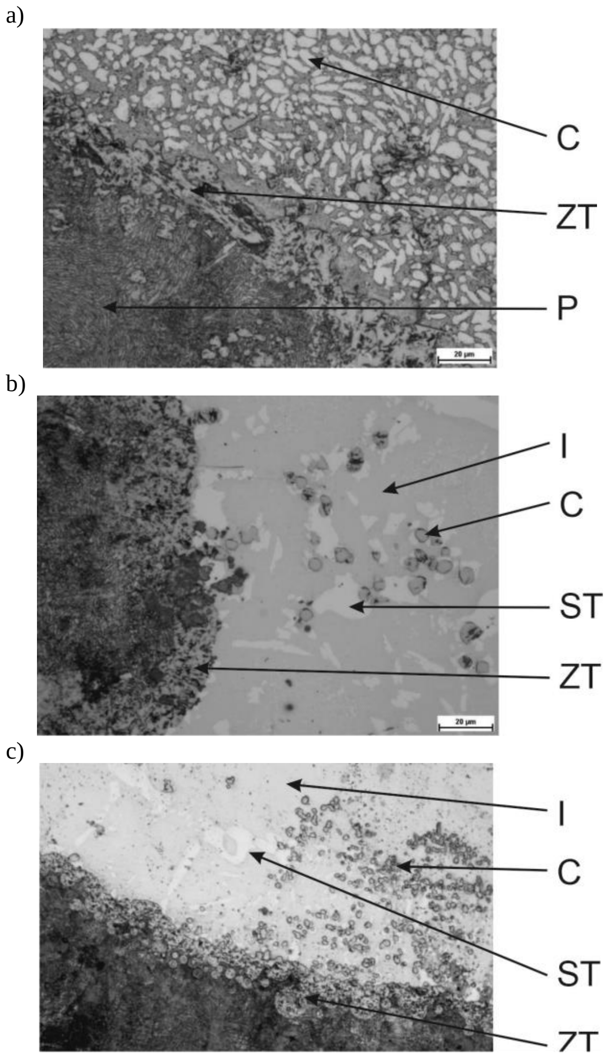


Fig. 8. The microstructure of layered bimetal casting: a) W-160-2.25; b) W-160-0; c) W-160-1.5; magnification 500x; C – titanium carbides; P – pearlite; I – insert; ST – solid of solution titanium; ZT – carbides-rich zone

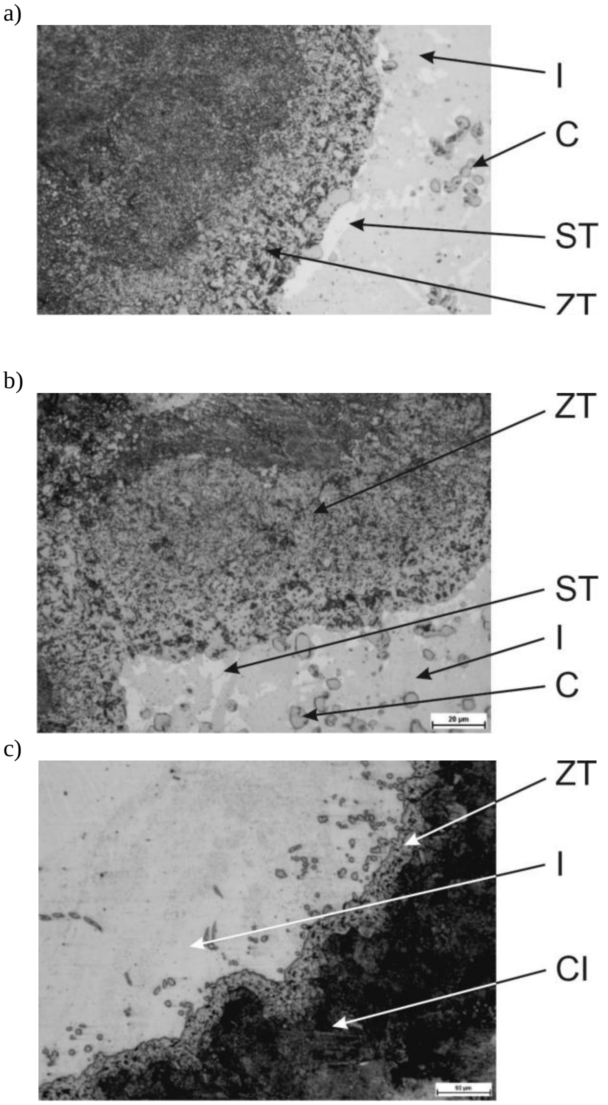


Fig. 9. The microstructure of layered bimetal casting: a) W-120-2.25; b) W-120-0; c) W-120-1.5; magnification 500x; C – titanium carbides; P – pearlite; I – insert; ST – solid of solution titanium; ZT – carbide-rich zone; CI – gray cast iron base

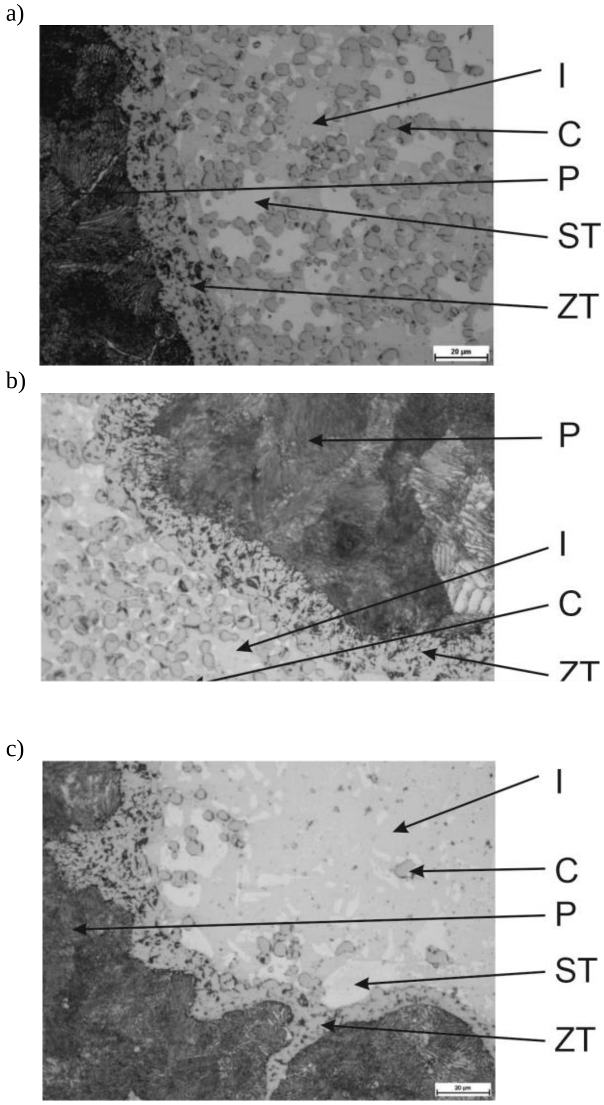


Fig. 10. The microstructure of layered bimetal casting: a) W-80-2.25; b) W-80-0; c) W-80-1.5; magnification 500x; C – titanium carbides; P – pearlite; I – insert; ST – solid of solution titanium; ZT – carbides-rich zone

No cracks were observed in any of the castings in the test zone. In bimetal casting W-160-2.25 no sharp transition between the composite materials was found – there is no visible boundary between the cast iron and titanium layers. Many precipitates appeared near the connection of the composite layers, and a new phase was formed at the layer boundary.

Fig. 11 presents the examples of connection zones of two materials – forming the bimetal connection – picture from a scanning electron microscope (SEM).

a)

b)

c)

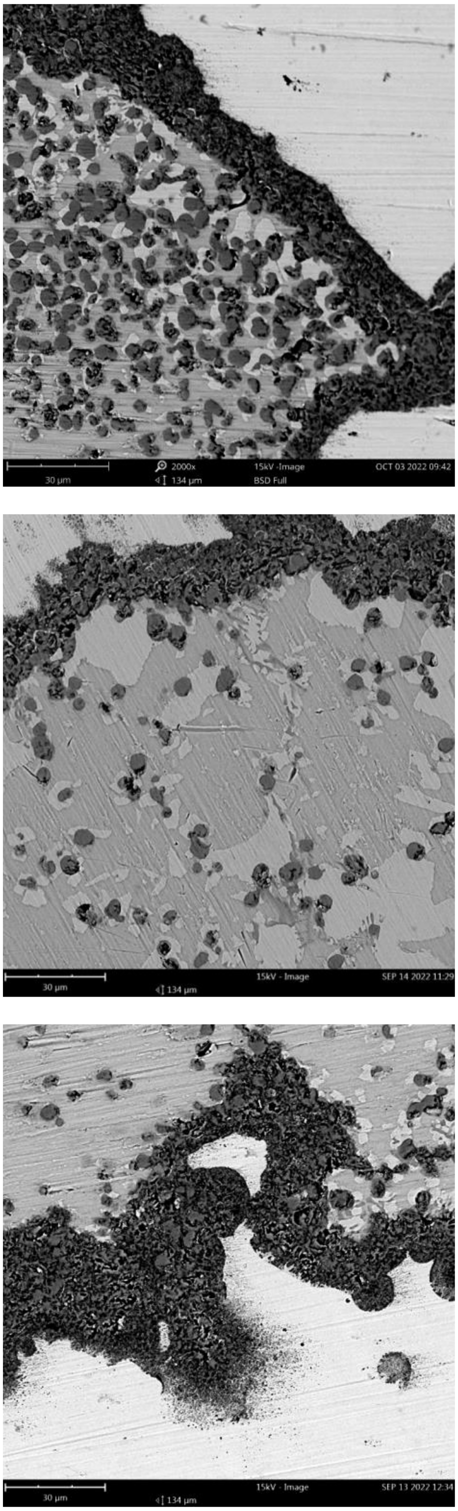


Fig. 11. Transition zone (insert – cast iron), SEM magnification 2000x; a) W-160-1.5; b) W-120-1.5; c) W-80-1.5

It was observed that with the increase in the casting size, the visible titanium carbide precipitates are loosely located on the casting surface, while in the smallest castings the layer of titanium carbide is better visible – individual particles occur on a smaller scale than in the others.

A point analysis of individual structure components was also performed (Fig. 12). The tests performed in the insert attachment site showed the presence of three areas with different chemical compositions. The first area called the insert matrix comprises the material resulting from the diffusion of elements, this is the residue from the insert. It contains a large proportion of titanium. The other area under consideration is the so-called solution consisting mainly of titanium and iron of similar content. This area requires further research. Another area, where titanium and carbon are the dominating elements, while their relative mass ratio corresponds to titanium carbides [15,16].

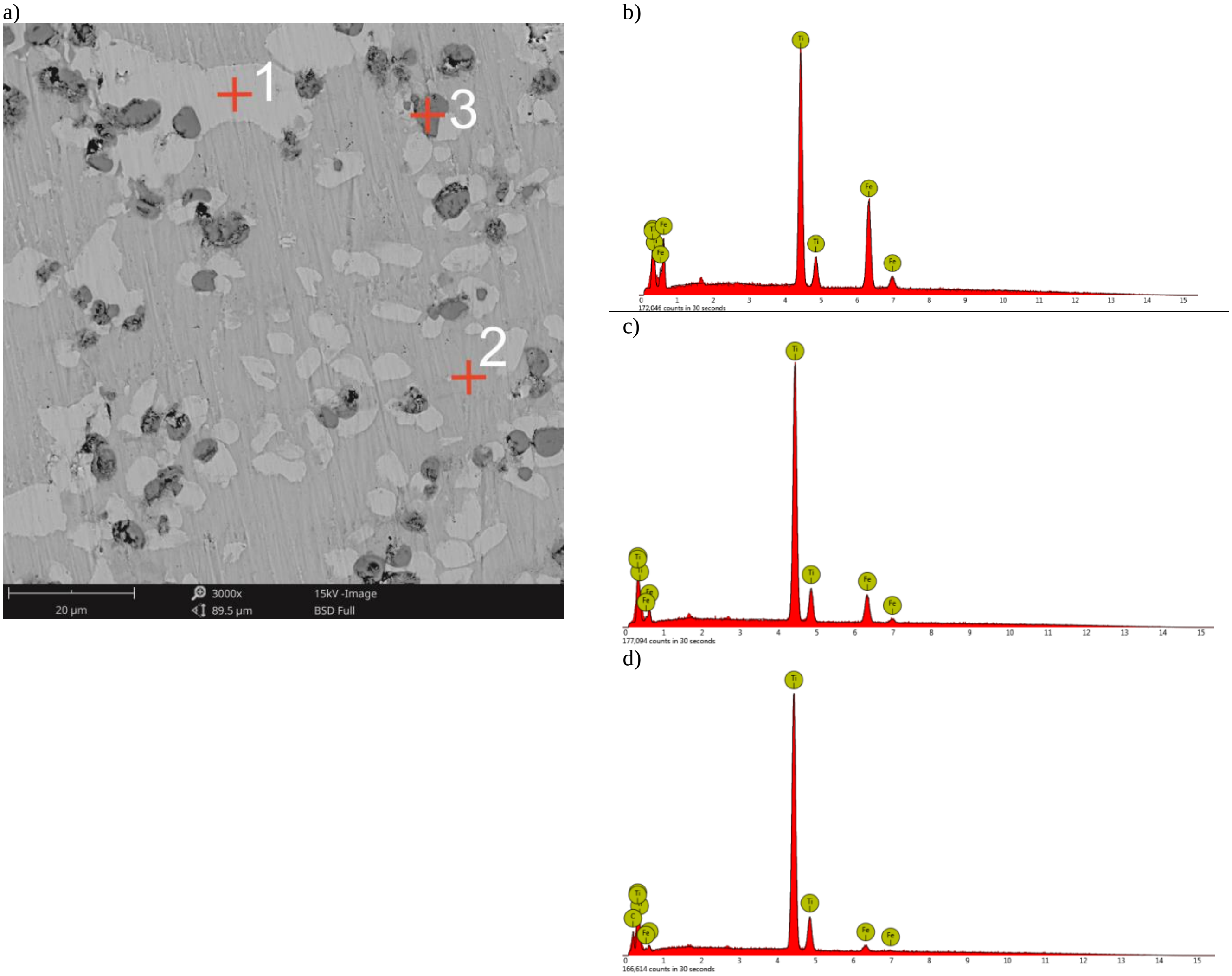
Layer thickness measurement

In order to verify the impact of the insert type (link thickness) on the bimetal layer thickness its measurement was performed within a single link using microscope. The results obtained are presented in Table 2.

Table 2.
Titanium layer thickness measurement

Casting No.	Measurement, mm				Average, mm
	1	2	3	4	
W-160-2,25	No measurements				
W-120-2,25	0,42	0,61	0,48	0,91	0,61
W-80-2,25	0,82	0,31	0,41	0,52	0,52
W-160-1,5	0,83	0,95	0,83	0,8	0,85
W-120-1,5	1,44	0,92	0,65	0,93	0,99
W-80-1,5	2,87	2,98	2,93	2,78	2,89
W-160-0	2,91	3,02	3,01	2,58	2,88
W-120-0	2,96	3,06	3,23	2,94	3,05
W-80-0	0,83	0,91	0,81	0,97	0,88

Measurements show a correlation between the thickness of layer and the type of insert. The greatest thickness of the layer occurs for the solid insert, it was comparable to and even greater than the link thickness (input material). For the W-160-2.25 casting it was impossible to take measurement due to the lack of clear phase boundary visibility. It was also observed that the highest layer thickness was obtained in 120 mm sized castings, comparing the same inserts for different casting thicknesses.



chemical element	point 1		point 2		point 3	
Fe	44,4	48,2	18,9	21,4	3,2	4,9
Ti	55,6	51,8	81,1	78,6	65,8	85,1
Si	–	–				
C	–	–			31,0	10,0
	Cp_a	Cp_m	Cp_a	Cp_m	Cp_a	Cp_m

Fig. 12. a) Connection microstructure SEM 3000x for sample W-160-2.25; b) the result of the EDS analysis at the point 1; c) EDS analysis result in point 3; d) EDS analysis result in point 5;
Cp_a – atomic concentration
Cp_m – mass concentration

3. Conclusions

The cast iron matrix composite with titanium reinforcement formed by casting methods ensures a permanent connection of layers for many types of titanium inserts. New phases appear in the connection zone, including titanium carbide. The MMC type layered composites allow us to combine the features of many metals, while the in-situ method makes it possible to obtain new phases in the production process. In addition, the 3D printing makes it possible to form titanium inserts with different sizes.

Microscopic studies revealed the presence of numerous titanium carbide precipitates near the titanium insert attachment site. It was also noticed that the structure obtained featured heterogeneous density of carbides, while their concentration was the highest in the place of dissolution and diffusion of the insert components (transition zone). In addition, the analysis of chemical composition showed that a new phase with a dominant share of titanium and iron was formed in the area under examination.

On the basis of the research, the following conclusions were drawn:

1. A permanent connection of cast iron matrix with the titanium insert reinforcement was obtained.
2. Precipitations of titanium carbide were formed in the area where matrix layers connected with the reinforcement.
3. The influence of titanium insert type and cast iron dimensions on the titanium thickness was noted.
4. It was noted that the layer thickness is irregular, while for the insert with the 2,25 mm inner opening no clear layer boundary was found.

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