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MANUFACTURING AND PROPERTIES OF Al-Al ALLOY BIMETALLIC COMPOSITES OBTAINED FROM POWDERS BY HOT EXTRUSION

This paper presents the process of manufacturing bimetallic composites in the shell-core system. Al17Si5Fe3Cu1.1Mg0.6Zr alloy powder was used for the shell. Pure aluminum was used as the core of the composite, respectively, in the form of a cast and then rolled rod, and in the form of a semi-finished product obtained from aluminum powder. The semi-finished powders were produced by means of the uniaxial hot pressing method. From the components prepared in this way, an extrusion charge was made by machining in an alloy shell-core system. Permanent bonding of the components and forming the required shape of the composites was carried out using direct hot extrusion under isothermal conditions. It was confirmed that the application of powder metallurgy technology for the production of one or both component materials makes it possible to conduct the extrusion of the components with significantly different plasticity without violating the cohesion of the layers. This approach made it possible to produce layered composites with high-strength properties of the outer layer and with a ductile core. The microstructural state of the components was evaluated, focusing on the continuity of the transition zone between the components. Observations of the separation lines between the layers revealed that the zone between the components was continuous, which was found for both composites, regardless of the examined cross-section. On this basis, it was concluded that the direct hot extrusion process, carried out under the adopted parameters, made it possible to combine the components very well. Selected properties of the layered composites were also determined. It was shown that the proposed method, combining powder metallurgy and hot forming technologies, makes it possible to obtain a continuous connection of components and produce products with properties significantly differentiating in the core and shell zones. These properties can be controlled by appropriate selection of the components, as well as by the method of manufacturing the core. Potential applications of the studied materials include the manufacture of bimetallic components for operation in conditions where significantly different properties of the outer zone and the core are required.

Keywords: **bimetallic composites, hot extrusion, powder metallurgy, aluminum, microstructure, properties**

INTRODUCTION

Bimetallic composite materials, which include lightweight metals or alloys, are now increasingly used as structural components, particularly in aerospace and automotive applications [1, 2]. A characteristic feature of these materials is a step change in the material properties of the individual components. As a result of applying an appropriate technological path, materials with different properties are combined in such a way that they form a new bimetallic product [3]. Bimetallic composites are used for such solutions where one material cannot meet all the properties required of the whole component [4]. By using components with appropriately selected characteristics, it is possible to produce a core-shell product that will have significantly different properties in the near-surface zone and the inner part. Systems of this type can combine the high strength and wear resistance of the near-surface zone with the light weight and good electrical conductivity of the core. Another example is to make a component with a stiff outer part and a ductile core. Currently, there is interest in sandwich composites made in various variants from lightweight aluminum and magnesium alloys, as well as from copper and other metals [5, 6]. Selective reinforcement can also lead to economic advantages as it makes it possible to obtain a product with the desired properties by using a more expensive material only in those zones where it is required, and a relatively less costly material in the rest of the volume. An example would be a composite that consists of an aluminum-silicon-type alloy and pure aluminum.

The basic factors determining the properties and functionality of sandwich composites include the properties of the materials from which the individual layers are made, the volume percentage of each layer, the way the layers are arranged, and the manufacturing method. When choosing the manufacturing path, it is important to remember that it must guarantee a very good quality connection between the individual layers, which is one of the key conditions for obtaining a high-quality composite. In addition, the surfaces of the components must be free of discontinuities. One method that offers the possibility of meeting these requirements is plastic processing, which can be carried out by hot extrusion, among other methods. Extrusion is one of the primary methods for producing tubes, rods, and sections from steel, nonferrous metals, and their alloys [7]. The advantage of extrusion is the favorable stress state in which compressive stresses dominate, allowing the flow of materials that are difficult to deform by other methods. Therefore, the process is well suited to produce composites with different combinations of layers [8]. The utilization of extrusion for the production of lightweight lagging-core composites can be an alternative to other methods employed to achieve differentiated product properties in the near-surface and inner zones, such as burnishing [9]. The benefits of this approach include the absence of the effect of strengthening by deformation and internal stresses, as well as the ability to produce finished products of a desired shape. In addition, an extrusion process carried out with the correctly selected parameters makes it possible to obtain very good quality connections between the layers, as presented in the results of research conducted by Zhao and Li using aluminum-silicon alloy components [10].

Commercial semi-finished products, usually metals or alloys cast and then shaped into sheets or bars, are most often applied as components to make sandwich composites. However, in the case of alloys of the aluminum-silicon group, it is difficult to obtain a fine-grained, homogeneous microstructure in this way. Therefore, an interesting alternative may be the usage of semi-finished products obtained by powder metallurgy technology [11]. The fabrication of layered composite components from alloy powders makes it possible to obtain a favorable microstructure with a small grain size, as demonstrated in works [12, 13]. It should also be considered that the course of the simultaneous hot extrusion of two different materials depends on the difference in their ductility [14, 15]. If this difference is significant, then there is a high probability of violating the cohesion of the material with lower ductility, creating non-uniform flow, or the formation of discontinuities on the separation surface. In such a case, the use of metal powders can be a favorable solution because the increased friction at the interface with the porous material can compensate for differences in the flow velocity of the materials.

The literature review indicates that combining powder metallurgy and hot forming technologies in a single technological pathway, leading to the production of lightweight bimetallic composites in an aluminum-aluminum system, with one or both components made of powder, may be a favorable solution, which was the motivation for undertaking our research on this topic.

MATERIALS AND METHODS

Materials used

The starting materials for the study were the atomized powder of the Al17Si5Fe3Cu1.1Mg0.6Zr alloy with a spherical particle shape, an atomized aluminum powder composed of irregularly shaped particles, and a cast and then rolled aluminum rod with a diameter of 35 mm in the delivery state. The powder morphology and microstructure of the aluminum rod are summarized in Figure 1.

a)
b)
c)

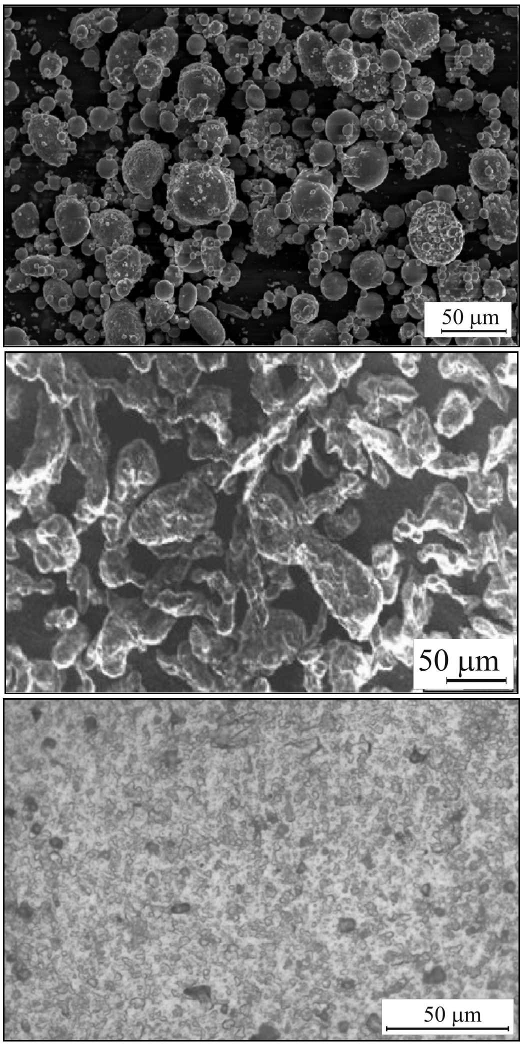

Fig. 1. a) Al17Si5Fe3Cu2Mg0.6Zr powder, b) aluminum powder, c) aluminum rod microstructure

Fabrication of composites

The adopted technological route for the manufacture of the bimetallic composites included the processes of uniaxial hot pressing of the Al17Si5Fe3Cu1.1Mg0.6Zr alloy and pure aluminum powders, making the core and shell by machining and then hot extrusion of the composite assemblies.

A setup consisting of a furnace, a cylinder-shaped die with an inner diameter of 37 mm, and a set of punches was used for hot pressing. The process was carried out under isothermal conditions. A constant temperature was maintained throughout the process, which was controlled by means of a thermocouple. The alloy and aluminum powders were compacted at the same temperature of 480°C. The compaction process was conducted on a ZD-100 hydraulic press. The powders were loaded into the die heated to the assumed temperature and held there for 15 minutes to achieve temperature stabilization. The applied pressure was 120 MPa for the alloy powder and 100 MPa for the aluminum powder. In both cases, the pressure was held for 4 minutes, which allowed the individual powder particles to be sintered together.

The next stage consisted in fabricating the component assemblies, which are the feedstock for hot extrusion (Fig. 2). Blank holes were made in the Al17Si5Fe3Cu1.1Mg0.6Zr alloy compacts to prepare the core containers, as shown in Figure 2b. The height of the containers was 22 mm, the outer diameter was 37 mm, the inner diameter was 23 mm and the thickness of the bottom was 7 mm. Cylindrical inserts with a diameter of 23 mm and a height of 15 mm were made from the aluminum sinters and an aluminum rod, which were placed in the containers (Fig. 2c).

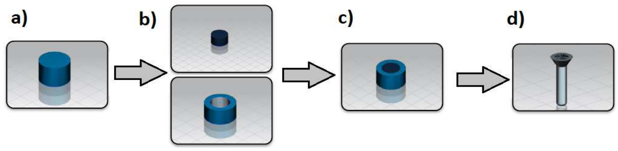

Fig. 2. Diagram of extrusion assembly fabrication: a), b) components, c) assembly, d) extruded bar

The fabrication of the layered composites involved hot extrusion of the assemblies (Fig. 2d). In addition, samples made of the individual materials (the aluminum sinters and the Al17Si5Fe3Cu1.1Mg0.6Zr alloy, as well as the aluminum rod) were also extruded. The aim was to compare the trends of force changes during the extrusion process of the composite components and their assemblies. The extrusion process was carried out under isothermal conditions, at the temperature of 480°C and with a linear speed of 0.2 mm/s. The samples were coated with graphite lubricant to reduce the coefficient of friction. An extrusion coefficient of $\lambda = 4.4$ was used, which made it possible to produce rods with a diameter of 18 mm. The dihedral angle in the deformation zone was 90°. During extrusion, the course of force changes as a function of the punch distance was measured. Rods made from the individual components were obtained, as well as bimetallic composites consisting of the Al17Si5Fe3Cu1.1Mg0.6Zr alloy shell and aluminum core, made by various methods. Figure 3 shows an example sample in the assembly and an extruded composite bar.

The microstructural state and selected properties of the components and the bimetallic composites were evaluated. The microstructure observations were carried out by light microscopy (Leica DM 4000M microscope). The specimens were mounted (Verso-Kit, Struers), ground (Struers films and sandpaper), polished (MD-Chem disc, OPS), and etched. Particular attention was paid to the quality of the boundary surface between components. The mechanical property tests included a compression test and hardness measurements. The hardness measurements were conducted using the Vickers method. The average HV values were determined from the results of 10 measurements. Non-standard compression testing of the composites, conducted to evaluate their failure course, was performed on a Zwick-Roell Z250 testing machine.

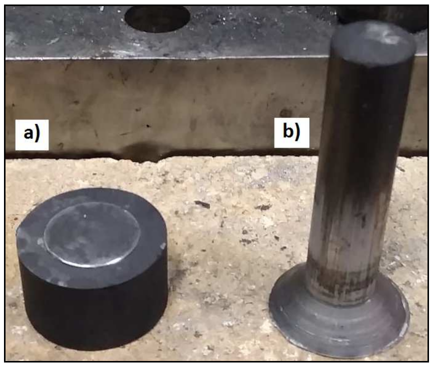

Fig. 3. Component assembly (a) and extruded bimetallic composite (b)

RESULTS AND DISCUSSION

Properties of sintered components

The relative density of the material sintered under pressure was determined by means of the Archimedes method. For the sinter obtained from the Al17Si5Fe3Cu1.1Mg0.6Zr alloy powder, the average relative density was 98.2%, and for the pure aluminum 97.8%. These values were considered sufficient to use the sinters as extrusion components.

Extrusion force

Figure 4 displays the extrusion curves as a function of punch displacement. The highest value of the force required for the extrusion process was found for the sintered Al17Si5Fe3Cu1.1Mg0.6Zr alloy. It was about 117 MPa during the laminar extrusion stage. The forces required for deforming the aluminum in this stage were lower and were about 80 MPa for the sinter and about 65 MPa for the cast rod, respectively. In the case of the extrusion of the material made of two components, in the first stage the force was similar to that recorded during extrusion of the Al17Si5Fe3Cu1.1Mg0.6Zr alloy, and then gradually decreased. This is because at the first stage of the process, the bottom of the container moved in the deformation zone, and later both components were shaped simultaneously. For this reason, the values in the range of punch displacement greater than 7 mm, which corresponds to the thickness of the Al17Si5Fe3Cu1.1Mg0.6Zr alloy container bottom, should be taken as the actual force values. The values of forces required for the extrusion process of the material made from powdered aluminum are about 20% higher than when aluminum in the form of a rod is used as the input. It should be assumed that the higher extrusion forces recorded in the case of hot deformation of the material obtained from the powders are the result of the presence of fine oxides originating from the surface of the powder particles and fragmentation during hot compaction and extrusion. A similar relationship was also found for the composites with the inner layer. The use of a core made by powder metallurgy increased the force required for extrusion compared to the system with the cast aluminum core.

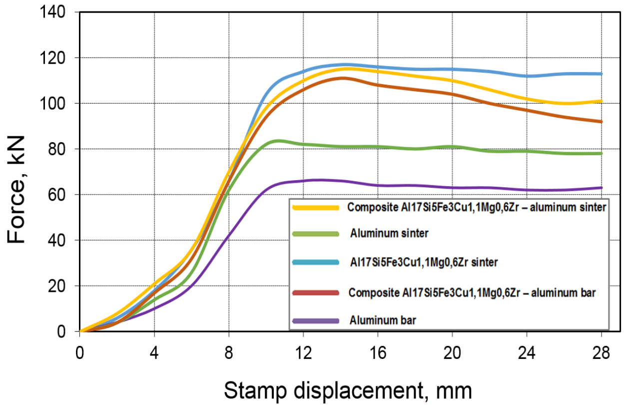

Fig. 4. Extrusion curves of component materials and bimetallic composites

Visual evaluation of composites

Visual evaluation of the hot extruded rods (Fig. 3) revealed no visible cracks, delamination, or discontinuities in the outer layer. It was found that the employed extrusion parameters allowed the fabrication of both bimetallic composites free of visible external defects. Thus, the correctness of the selection of the extrusion parameters, particularly the extrusion temperature, which was 480°C, was preliminarily confirmed. In selecting the temperature for this process, it was taken into account that the two-component materials (pure aluminum and the Al17Si5Fe3Cu1.1Mg0.6Zr alloy) differ in both their properties and melting temperatures. The alloy has significantly higher strength properties than the aluminum, as a result of which, the forces required for the extrusion process were significantly higher. Nevertheless, this alloy has a much lower temperature at which the liquid phase appears. Our previous research found that this temperature is about 505°C [16]. Therefore, at the adopted extrusion temperature of 480°C, the alloy had relatively high plasticity. The differences in the plasticity of the components demonstrated during force measurements (Fig. 4) were not significant enough to cause visible failure of the composite during extrusion. It is possible that the factor that reduced the differences in the flow of materials with different plasticity was the increased friction at the boundary surface of the porous material with the solid one, and especially at the separation surface of the two porous components, which stabilized the assembly. However, at this stage of the research, this was only a preliminary assessment that needed to be confirmed by means of microstructure observations.

Microstructure observations

The microstructures of the component materials obtained by hot sintering under pressure of the aluminum and aluminum alloy powders are shown in Figure 5. The micrographs of the extruded bimetallic composites, taken on longitudinal and transverse sections, are summarized in Figures 6 and 7. In the case of the composites taken on longitudinal sections, the direction of material flow is indicated by arrows. The state of the microstructure in the areas of the aluminum core and the Al17Si5Fe3Cu1.1Mg0.6Zr alloy shell, as well as in the transition zones between the components where attention was paid to the continuity of their connection, was evaluated.

a) b)

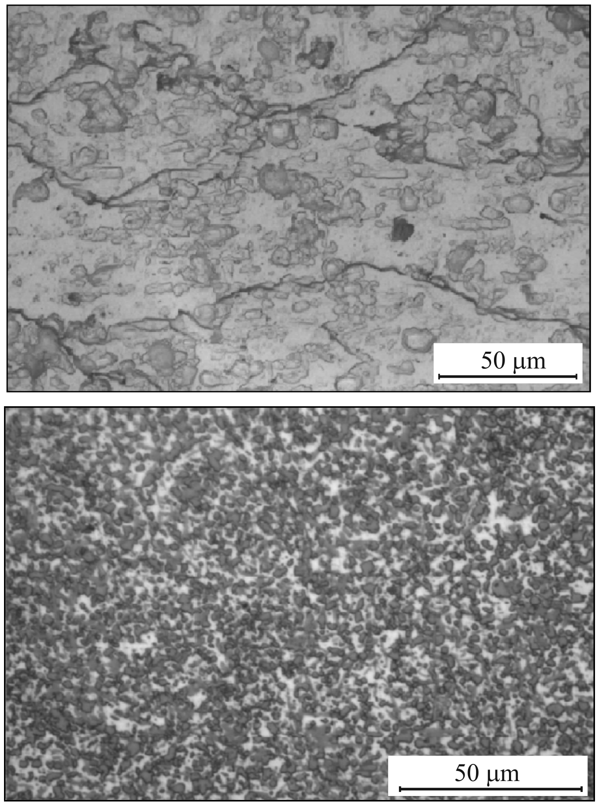

Fig. 5. Microstructures of component materials obtained by hot sintering under pressure of powders: a) aluminum and b) Al17Si5Fe3Cu1.1Mg0.6Zr alloy

The micrographs of the sinter made from aluminum powder (Fig. 5a) show the boundaries of the original powder particles, but no break in continuity was found in their areas. At these boundaries, fragmented oxides are visible, which probably caused the material to strengthen, and as a result, the force required for extrusion was higher. The microstructure of the Al17Si5Fe3Cu1.1Mg0.6Zr alloy sinter is fine-grained and homogeneous. Observations of the microstructure of both sinters (Fig. 5a,b) did not reveal the presence of pores, which qualitatively confirms the results of the relative density measurements of these products. In the case of both components, there was permanent fusion of the powder particles, which indicates that the parameters of the hot densification process of these materials were correct.

For both of the composite materials, the microstructure of the layers made of the Al17Si5Fe3Cu1.1Mg0.6Zr alloy is fine-grained. The grains are equiaxial and their size does not exceed 1 μm (Figs. 6b, c, e, f, 7b, c, e, f). For this reason, the distortion of the grains and their orientation according to the direction of flow is not visible. Observations of the layer made of sintered aluminum (Figs. 7a, c, d, e) revealed that plastic flow caused significant improvement in the quality of the microstructure of this material through disappearance of the clear boundaries of the original powder particles, visible on the microstructure of the sintered material (Fig. 5). The microstructure in each layer is homogeneous and does not differ significantly depending on the distance from the center of the cross-section or the change of observation points on the longitudinal sections. One of the reasons for this is the resulting isothermal conditions, the constant temperature of the material throughout the process, and the absence of the effect of cooling of the outer zones due to heat transfer to the tool and the environment. When observing the separation lines between the layers, no cracks or delamination were observed (Figs. 6cf and 7c, f). The transition zone between the components is consistent and continuous for both composites, regardless of the cross-section on which the observations were made. On this basis, it was concluded that the hot coextrusion process, carried out under the adopted parameters, enabled the component materials to be properly joined.

a) b) c) d) e) f)

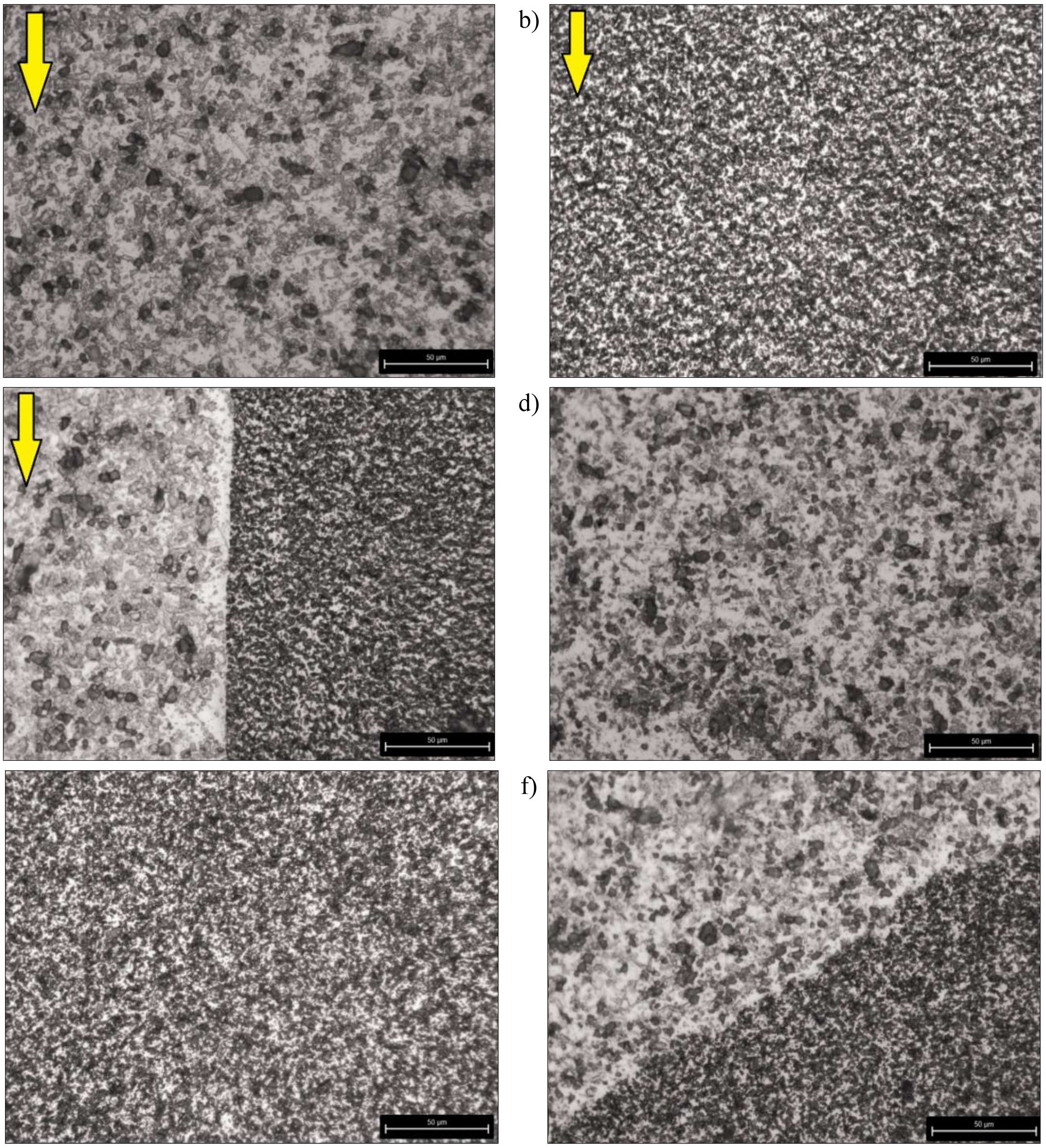

Fig. 6. Bimetallic composite obtained by extrusion at 480°C of component materials in Al17Si5Fe3Cu1.1Mg0.6Zr-cast aluminum rod sinter. Cross-sections: a, b, c longitudinal, d, e, f transverse. Zone: a, e sintered Al17Si5Fe3Cu1.1Mg0.6Zr, b, d sintered aluminum, c, e boundary between component materials. Etched

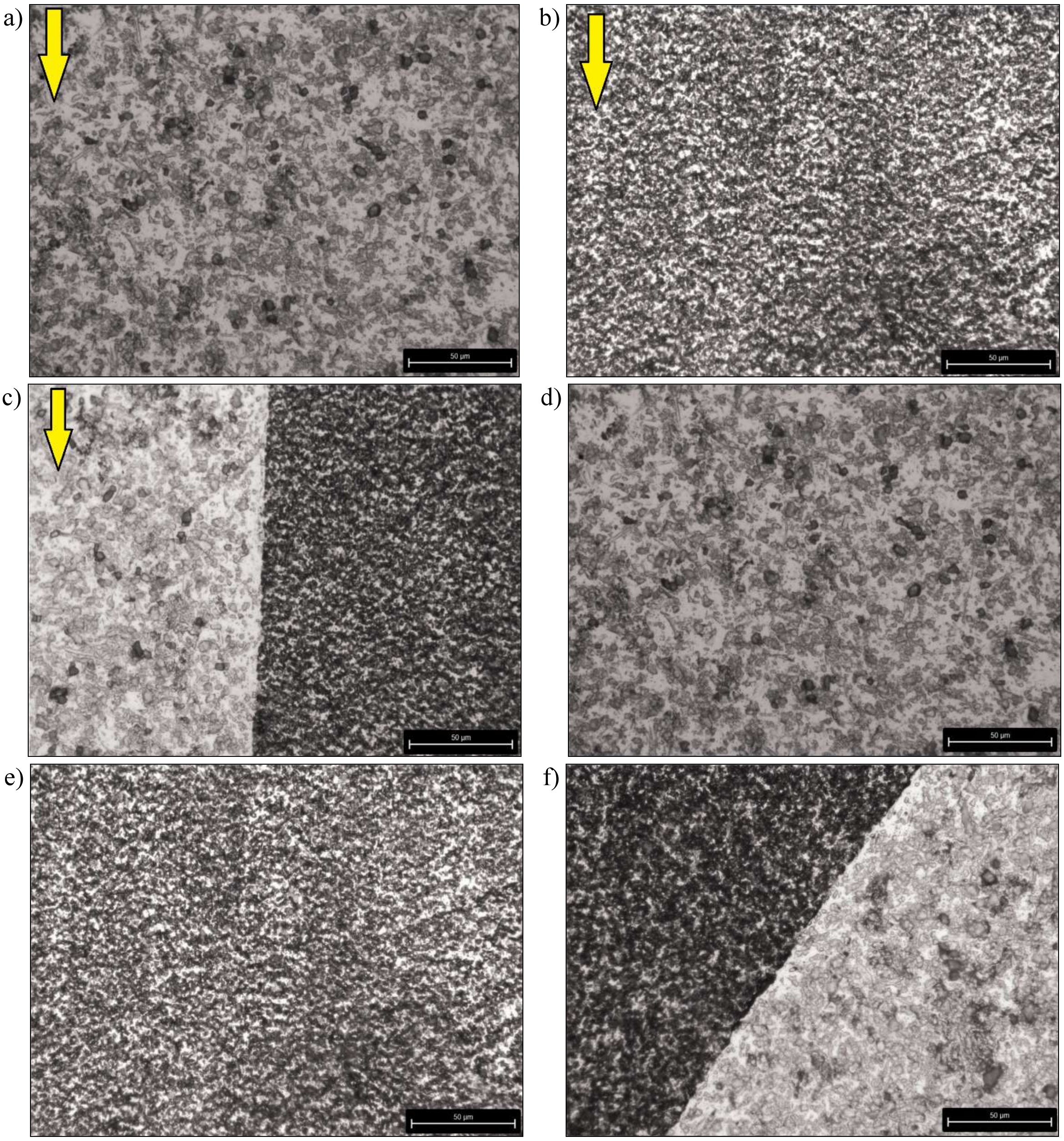

Fig. 7. Bimetallic composite obtained by extrusion at 480°C of components in Al17Si5Fe3Cu1.1Mg0.6Zr-aluminum sinter. Cross-sections: a, b, c longitudinal, d, e, f transverse. Zone: a, e Al17Si5Fe3Cu1.1Mg0.6Zr sinter, b, d aluminum sinter, c, e boundary between component materials. Etched

Compression test

The behavior of the bimetallic composites during a non-standard compression test conducted at room temperature between flat anvils was evaluated. The purpose of the test was to determine how the composites failed under such loading conditions. Owing to the structure of the composites, test specimens were cut from the extruded rods with a diameter of 18 mm and height of 25 mm. The specimens were compressed between flat anvils at a constant speed of 0.08 mm/s^{-1}. A photo of a deformed specimen with a marked crack is shown in Figure 8. It was found that in the case of both bimetallic composites, failure occurred due to cracks in the shell zone, which ran at an angle of 45° with respect to the axis of applied force. The cracks occurred in the part of the center of the height of the composite, which indicates that they were caused by tensile stresses in the peripheral part.

Fig. 8. Failed bimetallic composite sample in non-standard compression test

The occurrence of these stresses is due to the barrel effect. Nonetheless, the cohesion of the aluminum core was not affected, as expected. The method of fabricating the core did not affect the behavior of the composites during the test. The destruction of both composites followed a similar pattern and occurred at similar force values of about 9000 N.

Hardness tests

The hardness was measured in the zones of individual layers of both the bimetallic composites on longitudinal and transverse sections of the extruded rods. For comparison, HV hardness measurements were also made of the components that were used as the starting materials for the layers, (the pure aluminum sinter, the sintered Al17Si5Fe3Cu1.1Mg0.6Zr alloy, and the aluminum rod). The average HV values calculated from 10 measurements are summarized in Table 1.

TABLE 1. **Results of $HV_{0.5}$ hardness measurements of component materials and individual layers of bimetallic composites on longitudinal and transverse sections**

HV of semi-products			HV of individual layers of hot extruded bimetallic composites					
Al rod	Al sinter	Alloy sinter	Al rod layer – LS	Al rod layer - CS	Al sinter layer - LS	Al sinter layer – CS	Alloy sinter layer – LS	Alloy sinter layer – CS
18.7 ± 0.3	29.6 ± 0.3	176.1 ± 1.8	17.7 ± 0.5	17.3 ± 0.3	25.1 ± 1.5	24.5 ± 1.1	144.2 ± 4.6	143.9 ± 2.4

Abbreviations: LS – longitudinal section, CS – cross-section, alloy sinter – Al17Si5Fe3Cu1.1Mg0.6Zr alloy.

Based on a comparison of the HV values of the starting materials and the layers, it was found that the extrusion process carried out under isothermal conditions and at low speeds led to a decrease in hardness for all the materials. In the case of the cast aluminum the decrease was insignificant, while for the materials made from the powders it was pronounced, and amounted to 18% for the aluminum sinter and about 18% for the Al17Si5Fe3Cu1.1Mg0.6Zr alloy sinter, respectively. There were no significant differences in the results of successive measurements on the individual layers, as confirmed by the small spread of the HV values. This finding applies to measurements made on both longitudinal and transverse sections. The lack of variation of the HV values, for example, depending on the distance from the external surface or along the length, indicates the anisotropy of the products, which confirms the conclusions of the observations of the state of the microstructure.

CONCLUSIONS

Based on the results of the study, which included tests of the production of bimetallic composites in the shell-core system and evaluation of their properties, it was concluded that:

1. The use of powder metallurgy technology for the production of one or both component materials makes it possible to carry out the extrusion of components with significantly different plasticity without violating the cohesion of the layers.
2. Observations of the separation lines between the layers showed that the transition zone between the components was consistent and continuous, which was found for both composites, regardless of the examined cross-section. On this basis, it was concluded that the direct hot extrusion process, performed under the adopted parameters, made it possible to combine the components very well.
3. The microstructure of the individual composite layers is homogeneous and does not differ significantly on the studied cross sections. In the case of the Al17Si5Fe3Cu1.1Mg0.6Zr alloy outer layer, the grain size did not exceed 1 μm.
4. It has been shown that the proposed technological route for the production of aluminum bimetallic composites, based on extrusion under isothermal conditions of component materials made by powder metallurgy or in a sinter-casting system, makes it possible to produce good quality products.
5. Potential applications of the studied materials include the manufacture of bimetallic components for operation in conditions where significantly different properties of the outer zone and core are required.

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