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Possibility of Al-Cu composite manufacturing from fine metal fractions by recycling process

Określenie możliwości wytwarzania kompozytów Al-Cu w procesie recyklingu drobnych frakcji metali

Abstract

Plastic consolidation of highly fragmented materials is a cost-effective way to recover aluminum alloys. In this process, metal in the form of chips, powders, or ribbons omits the melting step that is typical for conventional scrap recycling; by that, it significantly reduces both energy expenses and material losses. By reducing the number of operations, the cost of labor and expenditures on environmental protection can be decreased. In addition, the solid bonding of metals in highly dispersed forms allows us to create heterogeneous structures that could be difficult to obtain in traditional processes. In the present study, the influence of the addition of Cu powder (99.7 wt.%) on the bonding quality of aluminum powder (99.7 wt.%) during hot extrusion is being examined. The examined materials contained aluminum powder with the addition of 5 wt.% of Cu powder. The mixture of these powders were cold compacted to produce an 80-mm-long charge for the extrusion process. Plastic consolidation was conducted at three different temperatures: 300°, 350°, and 400°C. As a result, rods 8 mm in diameter were obtained. Mechanical tests combined with microstructure observations and electrical conductivity tests were performed for the as-extruded materials.

Keywords: aluminum, copper, powder, plastic consolidation, electrical conductivity, Al-Cu composite

Streszczenie

Konsolidacja plastyczna silnie rozdrobnionych form materiałów jest ekonomicznie opłacalnym sposobem odzysku stopów aluminium. W procesie tym pomija się etap topienia, który jest integralną częścią recyklingu konwencjonalnego złomów metali takich jak wióry, proszki i taśmy. Umożliwia

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to znaczącą redukcję nakładów energetycznych oraz strat materiału. W wyniku zmniejszenia liczby operacji, koszty pracy oraz wydatki na ochronę środowiska mogą zostać znacznie zmniejszone. Dodatkowo konsolidacja plastyczna metali w stanie silnie rozproszonym pozwala uzyskać heterogeniczną strukturę, która może być trudna do otrzymania w tradycyjnych procesach. W niniejszej pracy badano jakość połączenia proszku Al z proszkiem Cu podczas wyciskania na gorąco (proszek Al i 5 wag.% proszku Cu). Wstępnie zagęszczony na zimno wsad o długości 80 mm wyciśnięto w trzech temperaturach: 350°C, 400°C, 450°C. W wyniku konsolidacji plastycznej otrzymano pręty o średnicy 8 mm. Dokonano obserwacji ich mikrostruktury, określono własności mechaniczne z próby jednoosiowego rozciągania oraz przeprowadzono pomiar przewodności elektrycznej.

Słowa kluczowe: aluminium, miedź, proszek, konsolidacja plastyczna, przewodność elektryczna, kompozyty Al-Cu

1. Introduction

Nowadays, composites are one of the fastest-developing groups of materials in the world. By joining different materials (e.g., metallic), it is possible to obtain products that possess the combined properties of its base components [1–7]. On the aluminum scrap market, waste in the form of foils, blisters, and different kinds of metal dust represents a significant share. Conventional recycling of this kind of scrap generates a high amount of material losses (e.g., drosses, risers, shrink holes), which may reach as much as 70% of the initial charge weight in some cases. By applying alternative processes such as plastic consolidation, it is possible to significantly reduce material losses to a few percent, along with the simultaneous lowering of energy consumption [8–10]. An additional advantage of the solid bonding technology is the manufacturing of final and semi-final products in just one operation. In the literature, a series of articles can be found concerning the solid bonding of materials like powders, chips, and Al-Cu composites by sintering [3], cold rolling [4, 5], or extrusion [6–10]. According to many publications, Al matrix composites with the addition of Cu powder are characterized not only by low density but also increased heat conduction and good corrosion resistance [1, 9–11]. However, Al-Cu composites manufactured by hot-extrusion induce the formation of intermetallic phases [e.g., Al_2Cu (θ), Al_2Cu_3(δ), Al_4Cu_9 (γ)], which have a negative influence both on the plasticity and electrical conductivity of the material [3, 11, 12]. Additional material defects that may occur during consolidation (such as porosities or cracks) may induce a further increase in resistivity.

2. Experimental procedure

Materials used for the extrusion process were commercial powders of aluminum (99.7 wt.% Al, mean grain size – 45 μm) and copper (99.7 wt.% Cu, mean grain size – 63 μm). According to the producer, powdered aluminum was obtained by air atomization. The globular shape of this powder is presented in Figure 1a. At the same time, copper powder is characterized by a dendritic structure, which is typical for materials obtained by the electrolytic method (Fig. 1b). In the first step of the experiment, both powders were mixed for 40 min in a shaker (with a proportion of 95 wt.% of Al and 5 wt.% of Cu). Subsequently, the mixture was subjected to pre-compacting under a pressure of 240 MPa. As a result, cylindrical billets 40 mm in diameter and 10 mm in height were produced. The as-compressed billets were then extruded at three different temperatures: 300°, 350°, and 400°C. As a reference material, a rod extruded at 400°C from a solid aluminum block was used. Each of the obtained rods had a diameter of 8 mm. The extrusion ratio was 25. Samples for further analysis were ground on sandpapers of gradations from 320 to 4000 and polished with a use of a STRUERS diamond suspension. The microstructure observation of a longitudinal cross-section was performed with the use of a HITACHI SU-70 electron microscope. In addition, an analysis of the chemical composition of the obtained intermetallic phases was performed with the use of EDS (Energy Dispersive Spectroscopy).

Microstructure observations were performed on a longitudinal cross-section with the use of the HITACHI SU-70 scanning electron microscope. A chemical-composition analysis of the mentioned intermetallic phases was conducted with the use of Energy Dispersive Spectroscopy (EDS).

A series of tensile test samples with a diameter of 6 mm and gauge length of 30 mm were machined from the as-extruded rods. Uniaxial tensile tests were carried out at room temperature at a constant strain rate of $8 \cdot 10^{-3}\ s^{-1}$ using a Zwick Z050 testing machine. Measurements of electrical conductivity was performed using a Thomson bridge on a 50-cm-length section of the as-extruded rods.

a) b)

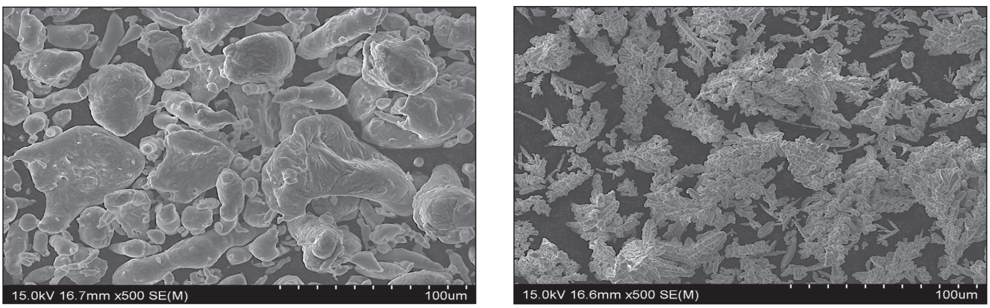

Fig. 1. Powder morphology of: a) aluminum; b) cooper powders

3. Results and discussion

3.1. Microstructure observation

In Figure 2, microstructure images of longitudinal cross-sections of the as-extruded rods have been presented. All profiles were characterized by the fibrous structure typical for the extrusion process. Higher magnifications also revealed the presence of discontinuities in the form of pores, whose sizes reached 1 μm in the case of the rod extruded at 300°C. As can be observed, increasing the extrusion temperature led to a distinct decrease in the maximum size of these voids. At 400°C, pores occur rarely, and their maximum diameter did not exceed 0.1 μm. The higher temperature also induced partial recrystallization in the samples. The examined microstructure did not reveal any form of delamination or piping defects.

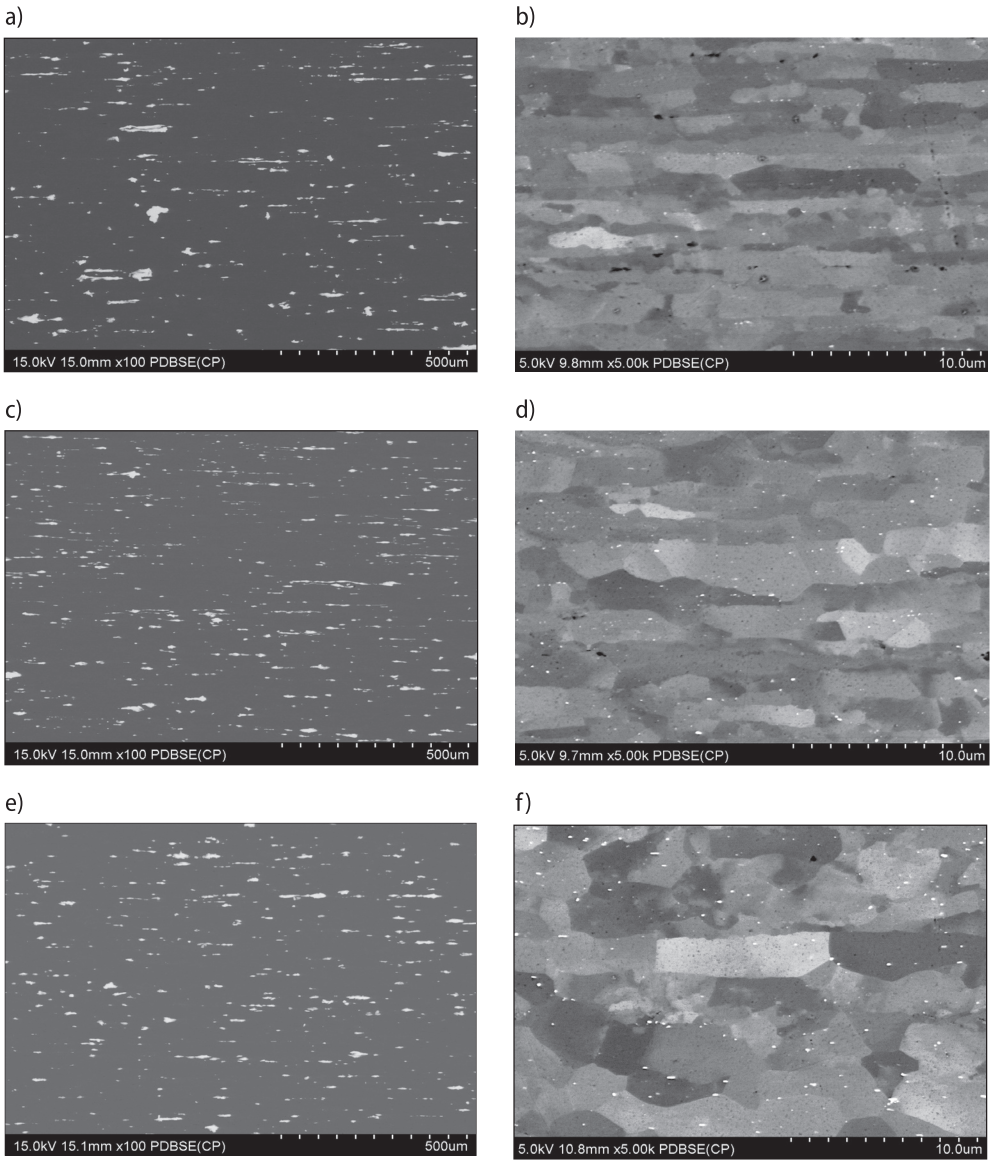

Fig. 2. Microstructure of $AlCu_5$ composite extruded at temperatures of: (a, b) 300°C; (c, d) 350°C; (e, f) 400°C

In Figure 3, changes in the chemical composition across the Al/Cu interface is presented. Due to the mutual diffusion of both elements, an intermetallic border around the white copper regions arose. Depending on the cooper content, intermetallic phases have a lighter or darker shade of gray. According to literature revision, lighter areas can be assigned to intermetallic Al_4Cu_9, while the darker region can be subjected to Al_2Cu [3, 11–15]

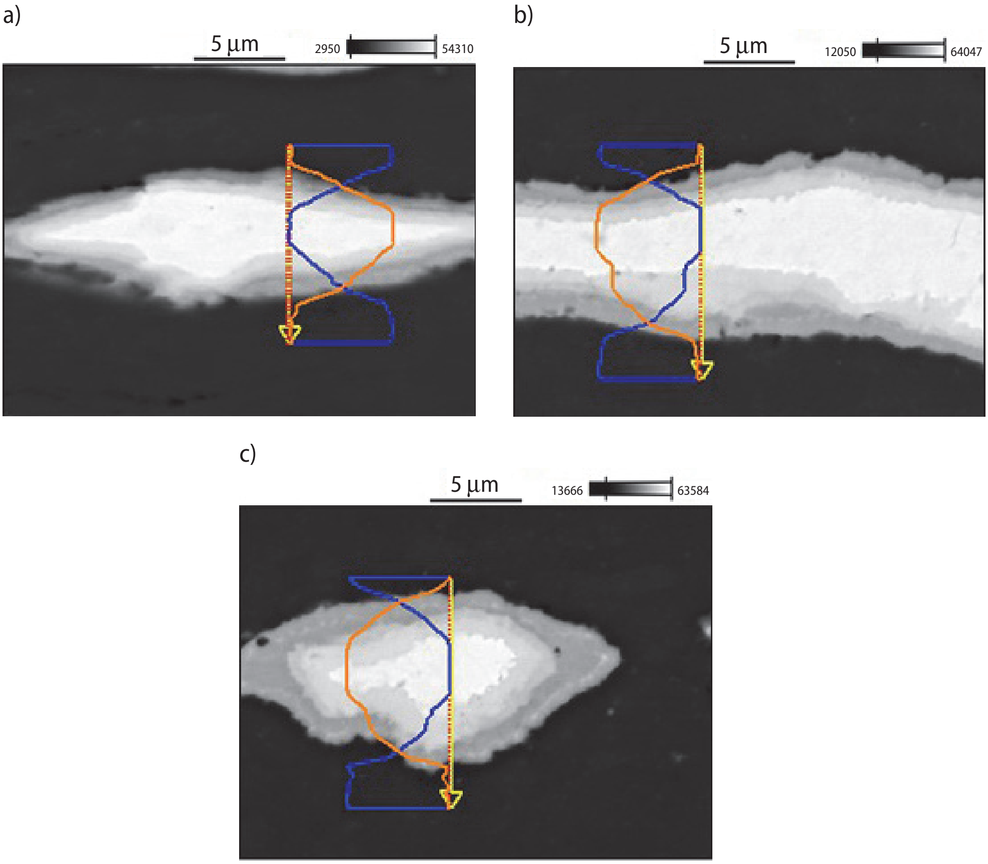

Fig. 3. Changes in chemical composition on cross-section of Al/Cu interface region: a) 300°C; b) 350°C; c) 400°C

3.2. Mechanical properties

The influence of temperature on the mechanical properties of the $AlCu_5$ composite are presented in Figure 4. The highest tensile strength can be found in the material extruded at a temperature of 300°C with UTS at a level of 189 MPA and a YS of 130 MPa. This gives a 75% increase in the ultimate tensile strength and 80% in the yield strength as compared to the profile extruded from solid material (Tab. 1). A further increase in temperature induce a decrease in UTS and YS to the respective levels of 174 MPa and 103 MPa (at 350°C) and 164 MPa and 85 MPa (at 400°C), respectively. The percentage of changes in the mechanical properties are listed in Table 1. A visible lowering of the mechanical properties can be attributed to the dynamic recrystallization processes occurring during extrusion. Simultaneously, grain growth leads to an increase in plastic properties. As can be observed, increasing the temperature by 100°C leads to a more than twofold increase in plasticity (with a slight decrease in the mechanical properties).

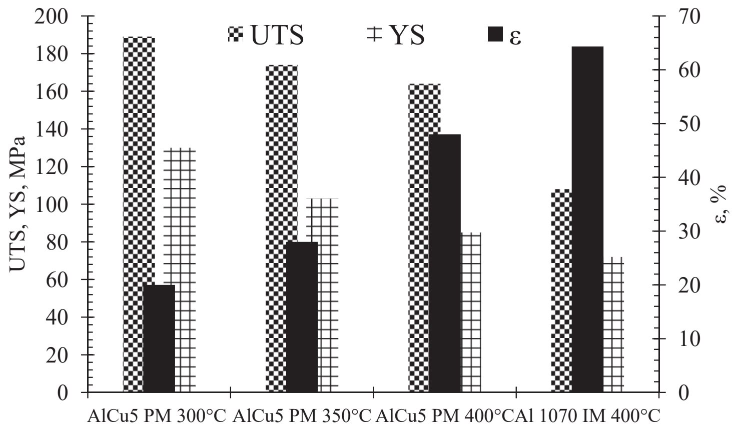

Fig. 4. Mechanical properties of all extruded AlCu5 composites as compared to reference Al material

Table 1. Overall changes in properties of solid bonded profiles as compared to reference material Al 1070 extruded at 400°C

Extrusion temperature of AlCu5 composite	UTS	YS	ε
300°C	75%	80%	69%
350°C	61%	43%	56%
400°C	51%	18%	25%

3.3. Electrical conductivity

The next stage of the research was the measurement of electrical conductivity. The presented bar graph in Figure 5 shows the electrical conductivity of aluminum (purity 99.99 wt.% [16]) and three rods of AlCu5 extruded under different temperature conditions. It can be noticed that the electrical conductivity of the AlCu5 rods extruded at 350° and 400°C are on a comparable level. However, the material extruded at 300°C revealed a slight drop in conductivity (to a value of 26.79 MS/m). By comparing the composites with analytically pure aluminum (Al-99.99 wt.%), electrical conductivity lowered by ~30%. This is due to the presence of intermetallic phases in the examined materials [12]. A slight increase in conductivity with temperature can be attributed to a higher consolidation level (lack of porosities) and lower amount of grain boundaries resulting from recrystallization.

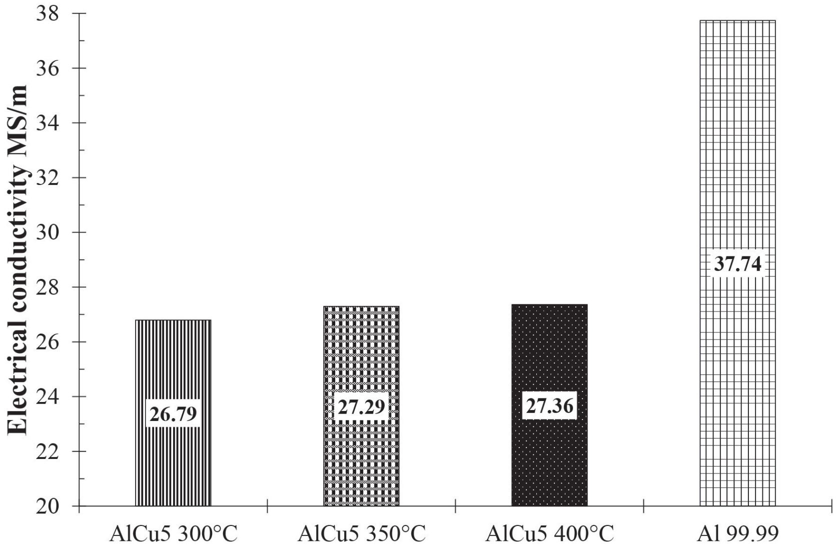

Fig. 5. Electrical conductivity of AlCu5 composite extruded at 300°C, 350°C, and 400°C

4. Conclusions

1. Plastic consolidation allows us to manufacture Al/Cu composites directly from powders
2. A lowering of mechanical properties extruded at higher temperatures arise from microstructure renewal.
3. The AlCu5 composite extruded at 400°C poses a more than twofold increase in plasticity ($\varepsilon = 48\%$) as compared to the material extruded at 300°C ($\varepsilon = 20\%$) while preserving its mechanical properties at a similar level.
4. Despite the increase in diffusion regions in the profiles extruded at higher temperatures, a slight increase in electrical conductivity is observed. This can be attributed to structure renewal and a lowering of the porosity level.

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