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DEVELOPMENT OF A CO-EXTRUDED Al-Ti BIMETAL COMPOSITE

RAZVOJ KOEKSTRUDIRANEGA BIMETALNEGA Al-Ti KOMPOZITA

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This study enhances the strength of the Al6061 alloy by adding Ti in the form of a rod using a thermomechanical process, which would be useful in making structures for aerospace and structural members. Two different properties of the material are joined together to form a new bimetallic material. Softer Al-6061 is used as a sleeve, and grade-II Ti is used as a core. They were prepared with a co-extrusion process at a temperature of 400 °C with different ratios of 2:1 and 2:0.5. The prepared substrates are analysed for characterization, hardness, tensile strength, and corrosion. The development of the diffusion layer is observed at the boundary of the Al-Ti material, and the bonding is improved. Compared to an aluminium alloy and a 2:1 bimetal composite, the co-extruded Al-Ti with a ratio of 2:0.5 bimetal composite ratio shows a better microstructure, mechanical, and tribological properties. It is concluded that the co-extrusion of Ti and Al is an efficient way to devise new composites with mechanical properties of 14 % and 19 %, respectively.

Keywords: extrusion, aluminium, titanium, mechanical properties; tribological properties

V članku avtorji opisujejo študijo načina izboljšanja trdnosti Al zlitine vrste Al6061 z dodatkom Ti v obliki kovinskih palic in uporabo termomehanskega procesa, ki se lahko uporablja za izdelavo letalskih in drugih strukturnih elementov. Dva materiala z različnima mehanskima lastnostima so avtorji spojili skupaj v novo bimetalno strukturo oziroma kompozitni material. Mehkejšo Al zlitino Al-6061 so uporabili kot rokav in titan kakovosti Ti II kot sredico. Bimetalni material so avtorji izdelali s postopkom koekstruzije oziroma istočasnega iztiskovanja pri temperaturi 400 °C in pri dveh različnih razmerjih (2:1 in 2:0,5). Izdelane preizkušance so nato mehansko okarakterizirali. Določili so njihovo trdoto, trdnost, tribološke lastnosti in odpornost proti koroziji. Opazovali so razvoj difuzijskega spoja bimetala na meji Al-Ti in ugotovili, da je prišlo do izboljšanja difuzijske vezave. Primerjava kompozitnega bimetala, izdelanega pri razmerju Al-Ti 2:1 z materialom izdelanem pri razmerju 2:0,5 je pokazala, da ima slednji boljšo mikrostrukturo, mehanske in tribološke lastnosti. Avtorji v zaključku tega članka poudarjajo, da je koekstruzija Ti v Al učinkovita pot za izdelavo novih kompozitov z odličnimi mehanskimi lastnnostmi. V raziskavi se je meja plastičnosti izdelanega bimetalnega kompozita v primeru uporabe razmerja 2:0,5 izboljšala za 14 % in natezna trdnost za 19 % v primerjavi z uporabo razmerja 2:1.

Ključne besede: ekstruzija, aluminij, titan, mehanske lastnosti, korozija in tribologija

1 INTRODUCTION

Aluminium alloys have excellent properties like low density, specific strength at a high level and better corrosion-resistance behavior.[1] It become a vital material in various industries due to these extremely beneficial properties. Aluminium alloys are used to fabricate primary components, accessories, and substitutes in aerospace and automotive. Aluminium grade 6061 would be preferred among the aluminium alloy family, as it has medium strength, good formability, corrosion resistance, and it is economical.[2] The strength of aluminium alloys can be enhanced by adding a suitable reinforcement to develop an Al-composite material.[3.] The excellent strength and corrosion resistance of titanium (Ti) make it the perfect reinforcing material.[4,5] While Ti and Al6061 are joined using the traditional welding process, localized failure occurs due to grain growth and welding defects. Thus, there is a need to explore the various metal-forming processes to join various materials like rolling and extrusion to improvise and attain the properties required for specific applications.[6] When comparing the functional and mechanical characteristics of bimetallic (co-extruded) and single metallic materials, single metallic materials have gained a lot of attention recently.[7–9]

The polycrystalline intermetallic phase of $TiAl_3$ is developed in the zone of bonding, and the authors observed that it depends on the used material's plasticity and temperature, controlled during the process. While the co-extrusion process was taking place, as a result of thermomechanical effects, it was observed that twinning occurred, which was parallel to the zone of bonding.[10,11] The significance of the materials that were incorporated into the applications is influenced by the factors of the co-extrusion process. The design of the die, the inlet and

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outlet ratio of the die, the dimensions of the billet, the pressure at which it is being operated, and the temperature are the vital parameters in the co-extrusion process.[12–14]

Solid-liquid and solid-solid are the two leading methods for manufacturing hybrid composites. In casting, compound castings were employed to prepare difficult shapes and the tough interface between the sleeve and the core. For better bonding between the liquid and solid phases, the compound casting method gets more attention from researchers. The process of extruding two or more materials at a time to get a single bimetal composite is called co-extrusion. Earlier, researchers focused on materials such as Al/Cu, Al/Ti, and Al/Mg for the formation of diffusion layers. However, during loading, defects like cracking and debonding can occur. It can be overcome by increasing the diffusion time according to Fick's law of diffusion, thus exhibiting good interface properties. Gecu and Karaaslan optimized the working temperature to manufacture the bimetal composite to attain supreme wear and corrosion resistance.[15] To enhance the interfacial bonding between Al and Al bimetal after a T6 treatment, the shear strength of the interfacial region and hardness is improved by the heat-treatment process.[16] Li et al. investigated the bimetal clad-plates using a friction-welding method and tested them for the bonding strength at the interfacial layer. A multi-island-like structure is observed at the interface, and Al_3Ti phase regions improved the adhesive properties.[17] To extend the application of mg composite material, bimetal composites were prepared using an insert-moulding machine. The process parameters are optimized to obtain a significant output. The tensile strength of the prepared bimetal increases to 100 MPa, which is close to the tensile strength value of the as-cast AZ91 magnesium alloy.[18] The advanced way of exploring the interfacial bonding mechanism is possible using Ansys software by hydrodynamics and arbitrary Lagrangian-Eulerian.[19] Garbacz et al. reported a wear case study of hydrostatic extrusion. A significant improvement in the tribological and frictional properties was observed from the study.[20] Thus, the joining of aluminium and titanium using various engineering methods is increasing day by day to meet the demand for several applications in industry. There is minimal literature available about adding Ti to the Al6061 alloy. Also, most of the studies using a casting technology for adding Ti to Al alloy. But in this study, an attempt was made to add Ti in a rod form to the aluminium alloy by a thermomechanical process to make a better metallurgical bond, which enhanced the mechanical and corrosion properties better than the parent Al 6061 alloy as well as cast alloys.

In this study, an Ai-Ti bimetal rod is fabricated by co-extruding with a smooth transition at the interface of the material. To understand the nature of the bonding, mechanical and tribological changes in the material characterization, hardness, compression strength, corrosion, and wear resistance are systematically analysed by following the standards in the test methods. The morphology study is to analyse the influence of the interfacial bonding between the sleeve and the core.

2 EXPERIMENTAL PROCEDURE

The aluminium Al6061 rods were purchased, and a wire form of titanium grade-II materials was used. The compositions of both the Al and Ti materials are given in **Table 1** and **Table 2**. Initially, the materials were machined and made to a billet size of 30 mm in diameter and a height of 30 mm. A Digital Vernier calliper was used to evaluate the dimensions, and the tolerance limits were set at 0.05 mm. A total of 12 holes with a diameter of 2 mm and a depth of 29 mm were drilled in the billet using a conventional drilling operation (**Figure 1**). The co-extrusion die angle was kept constant throughout the billet to ensure a uniform material flow. It is assumed that the drilled holes do not have any dirt or debris, thus affirming its fitness, and then the insertion of the wires of titanium.

A preheating temperature of 400 °C was maintained on the substrates for 3 h. Simultaneously, the die and container were also heated to fix the temperature to 450 °C.[21] Furthermore, the co-extrusion operation was conducted at a rate of 1 mm/s and with a force of 10 MN, which was the minimum. Furthermore, the lubricant used was graphite. One set of co-extrusion with 2:1 and the variation of the co-extrusion ratio was conducted (referred to as sample 1), and another set of co-extrusion with 2:0.5 as the variation of the co-extrusion ratio was conducted (sample 2). The microstructures of the extruded samples were analysed using a scanning electron microscope (SEM), an optical microscope, and an energy-dispersive X-ray analysis (EDX) to perform the morphological and surface elemental studies, respectively. The extruded samples were measured for microhardness (as per ASTM E384) and tensile strength (as per ASTM E8M-00b) using a Wilson hardness tester and

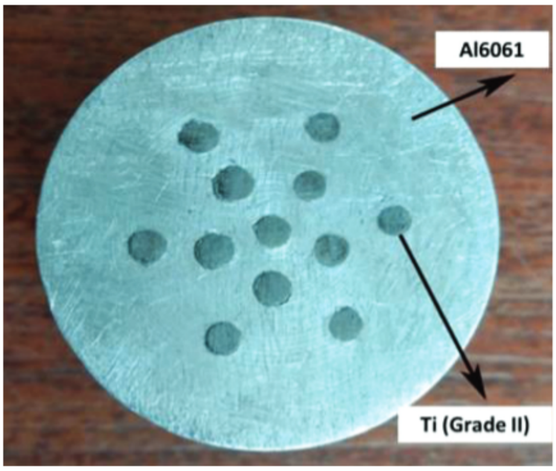

Figure 1: Al6061 as sleeve and grade-II Ti as core before co-extrusion

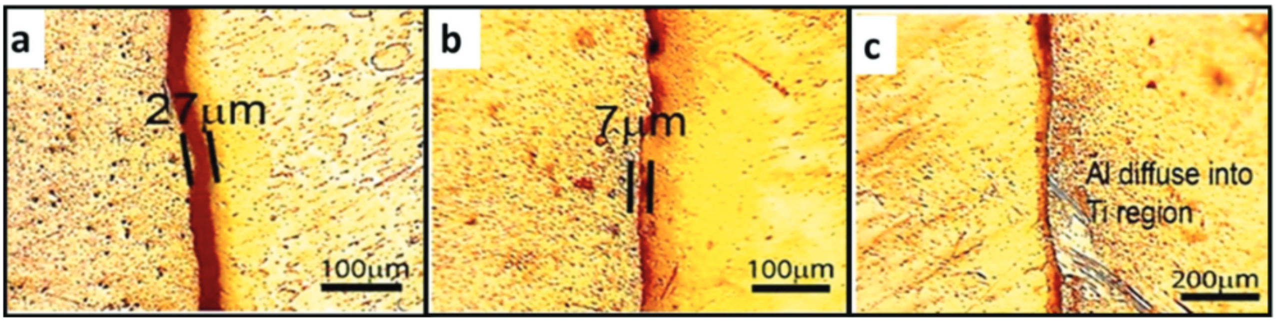

Figure 2: Co-extruded microstructure: a) sample 1, b) sample 2, c) sample 2 Al diffusion into Ti region

a universal testing machine (UTM) Model: Tinus-Olsen, Make UK. The corrosion test (as per ASTM G102-89) was conducted in an electrochemical workstation (Model SP-150, Biologic instrument, Make France) using three different electrodes. Platinum wire, the sample, and calomel are used as the cathode, anode, and reference electrodes, respectively.

Table 1: Al6061 alloy composition in *w*/%

Al	Si	Fe	Cu	Ni	Mn	Zn	Mg	Cr
97.78	0.96	0.28	0.12	0.05	0.04	0.06	0.61	0.10

Table 2: Elemental composition of Ti Grade II alloy in *w*/%

Ti	O	Fe	C	N	H
Balance	0.24	0.31	0.1	0.03	0.015

3 RESULTS AND DISCUSSION

3.1 Morphological analysis of the co-extruded Al-Ti substrates

The co-extruded sample 1 and sample 2 microstructures are shown in **Figure 2**. An interface thickness of (27 ± 7) µm is observed in sample 1 (**Figure 2a**), and it is observed that no diffusion occurred between the Al and Ti. It is also evident from the EDX analysis that diffusion was absent, which showed Al only at the interface (**Figure 3a** and **3c**). In sample 2, the interface thickness was observed to be (7 ± 1.5) µm, and the diffusion zone was found to be uniform, as shown in **Figure 2b**. The interfacial bonding between the Al and Ti is observed in the region shown in **Figure 2c**. The EDX investigation revealed the formation of the Al_2Ti intermetallic phase. Grade-II titanium shows the grain structure of a polyhe-

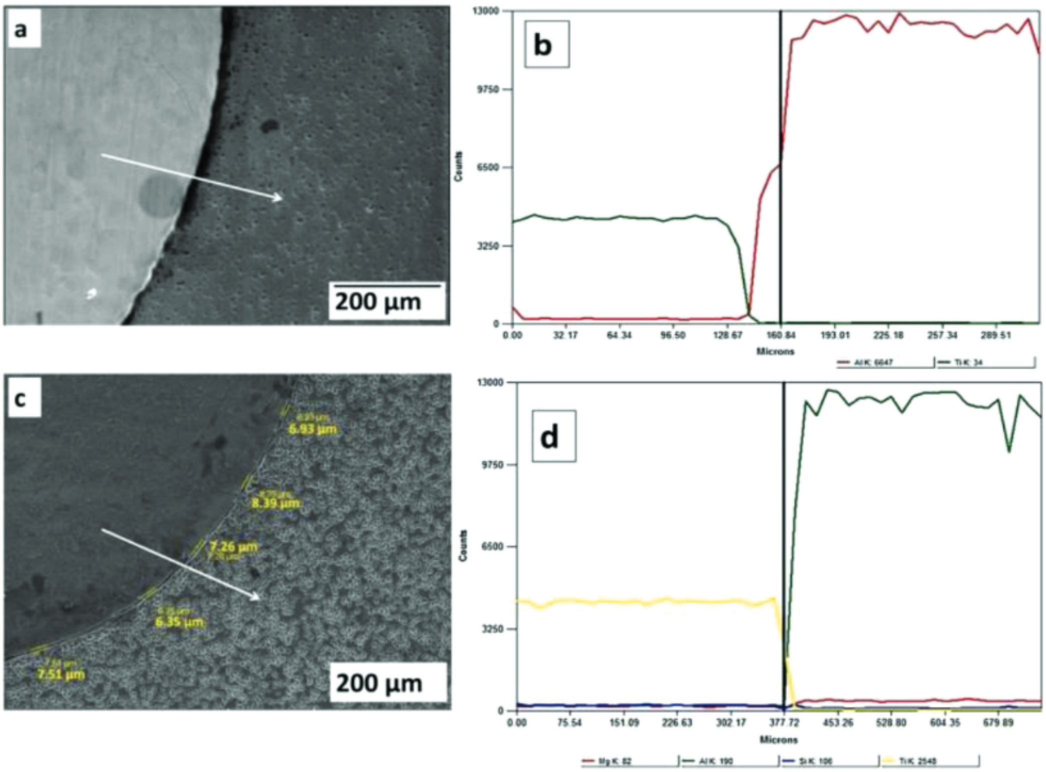

Figure 3: a) SEM micrograph of Sample 1, b) EDX analysis of sample 1, c) SEM micrograph of sample 2, d) EDX analysis of sample 2

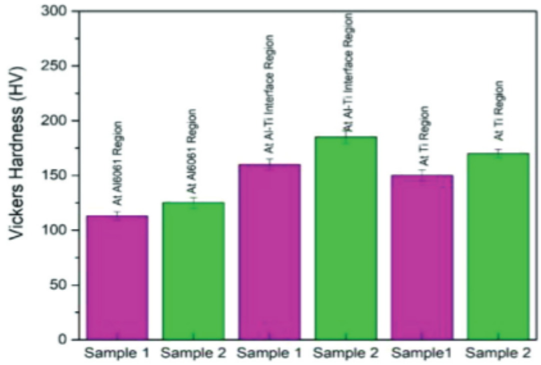

Figure 4: Hardness of co-extruded samples

dral shape, whereas the Al 6061 alloy illustrates the grain structure of the coarsened shape. At the bonding zone and submicron-sized precipitates in aluminium shows similar grey value. The primary reason for the improved mechanical and tribological properties is the large quantity of Al atoms fused with Ti atoms because of high pressure to produce high strength at the bonded region. During the co-extrusion process, the die diameter is reduced and hence exerts a high pressure; the Al material gets dispersed into titanium material more than sample 1 because of the inter-dispersion of titanium and aluminium atoms.[22] **Figure 3a** and **3c** show SEM images of the extruded samples, which show Al area interface bonding area and the Ti area after extrusion, and EDX taken using the line-scanning method, the scanning is made along the lines as indicated by arrows in these figures. The better interfacial bonding between Al and Ti is also confined by the EDX spectra line scanning (**Figure 3b** and **3d**). Hence, the interfacial bonding is better in the sample-2 co-extrusion process compared to sample 1.

3.2 Microhardness and corrosion behaviour of extruded Al-Ti samples

The prepared substrates were tested for microhardness using a Vickers hardness tester for samples 1 and 2. The hardness was tested on the substrates at three different locations: (i). At Al alloy (ii), in the Ti alloy, and (iii) in the region where the Al and Ti merge due to applied pressure. The hardness values of 111 HV, 161 HV, and 151 HV were observed in sample 1 at the Al base, interface, and Ti base regions. Similarly, sample 2 was also measured for hardness. The values are 126 HV, 185.4 HV, and 176 HV for the same equivalent regions (**Figure 4**). Sample 1 and sample 2 were compared for their hardness values, and we observed that the hardness value of sample 2 is higher in all the regions due to the higher strain energy produced in the lower co-extrusion ratio, as discussed above.

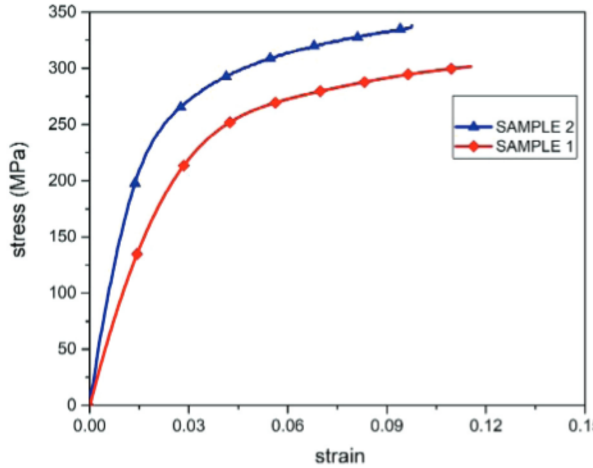

Figure 5: Stress-strain relationship of co-extruded samples

Furthermore, metallic bonds of Al and Ti were formed at the interface region, which was also evident during the microstructural analysis. Samples 1 and 2 were tested for the stress and strain values using the UTM, and the stress-strain curve obtained is shown in **Figure 5**. The yield strength of sample 2 was 250 MPa, whereas the yield strength of sample 1 was 215 MPa, which indicates a 14 % increase in the yield strength of sample 2. Similarly, sample 2 has a 19 % higher strength than sample 1, which occurred because of proper diffusion with high strain energy, which was induced in conjunction with a lower co-extrusion ratio. However, there was a slight decrease in the ductility in sample 2 compared with sample 1 (refer to **Table 3**). **Figure 6** shows the surface of the fractured area in the interface region of

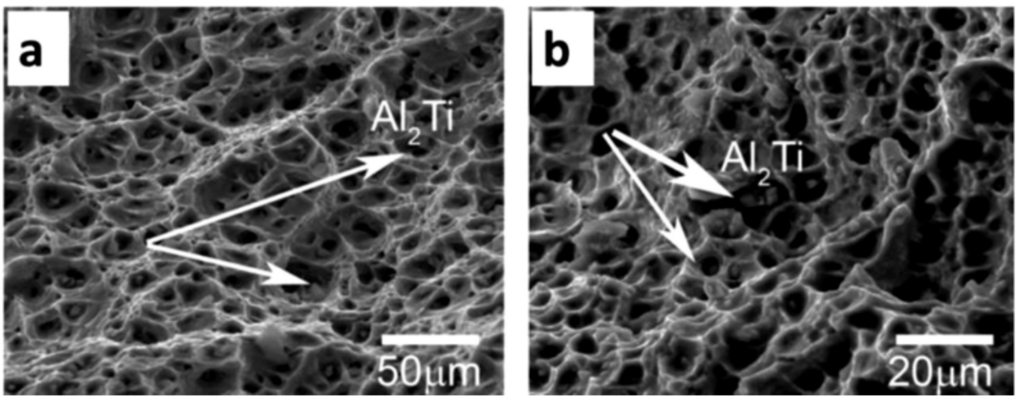

Figure 6: Fractography of: a) sample 1 b) sample 2

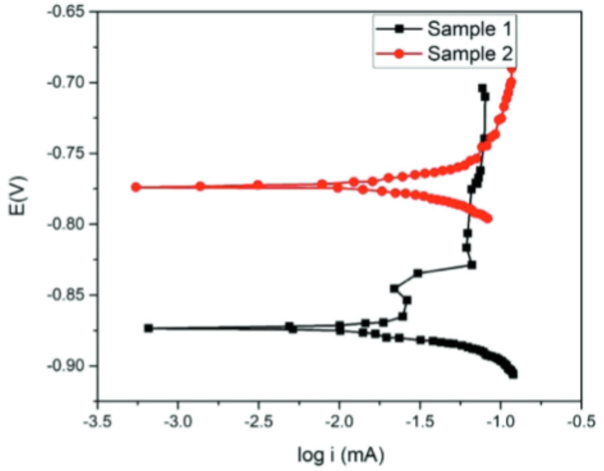

Figure 7: Tafel plot of co-extruded samples

sample 2 due to the improved load-bearing capabilities from the matrix to reinforcement. Many deep dimples are shown in the fracture surface, and fracture occurred in the regions of Al_2Ti.

Table 3: Results from co-extruded samples

Description	Yield Strength (MPa)	Ultimate Strength (MPa)	Ductility (%)
Sample 1	214	274	11.4
Sample 2	251	339	10.2

The corrosion study was conducted using the electrochemical polarization test method to check the substrate's corrosion resistance. The substrates go through the open circuit potential (OCP) test for 30 min at a scanning rate of 0.5 mV/s. The experiment is conducted at room temperature and pressure. The Tafel plots are generated using computer-integrated software. **Table 4** lists the test results of the electrochemical polarization test, in which it was observed that sample 2 had a lower corrosion rate than sample 1. Sample 1 had a higher corrosion rate because of improper diffusion and the void formation between the interfaces of the Al and Ti.

Table 4: Electrochemical test results of co-extruded samples

description	E_{corr}/V	I_{corr}/(A·cm^{-2})	corrosion rate (mm/y)
Sample 1	–0.767	3.126×10^{-6}	2.728×10^{-2}
Sample 2	–0.868	3.671×10^{-7}	1.014×10^{-3}

4 CONCLUSIONS

In this study the co-extrusion of Al6061 and grade-II Ti was conducted at two distinct ratios (2:1 and 2:0.5). It was followed by morphological characterization, mechanical properties, and studies of the corrosion resistance. The findings are listed below.

The sample 1 (Al/Ti) interface thickness was 27 µm, and the sample 2 interface thickness was observed to be 7 µm. In sample 2, the co-extrusion ratio is low, the die exit pressure is high, and thus the aluminium has an even diffusion bond with titanium, as shown in the EDX.

Compared to sample 1, the microhardness and tensile properties of sample 2 are superior. The higher microhardness value of 185 HV was obtained in the interfacial region, and the maximum values of the yield and ultimate tensile strength of sample 2 are 251 MPa and 339 MPa, respectively. The reason behind the improved properties could be the development of an increased strain energy in the die, which has a ratio of extraction of 2:0.5 and the formation of Al_2Ti at the interface.

In sample 2, the corrosion resistance of the prepared material was significantly improved. It has a lower corrosion rate of 1.014×10^{-3} mm/y, and a higher corrosion rate is obtained for sample 1, where the value is 2.728×10^{-2} mm/y. The values were obtained from the Tafel plot and measured using an electrochemical polarization test. Longer life can be achieved for the structural materials through the process of co-extrusion with a lower co-extrusion ratio.

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