Investigation on Microstructure and Hardness of Aluminium-Aluminium Oxide Functionally Graded Material

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Abstract. This study investigated the microstructure and hardness of aluminium-aluminium oxide (Al-Al_2O_3) functionally graded material (FGM). Preparation of metal-ceramic functionally graded material was carried out fol- lowing powder metallurgy (PM) route. Four-layered aluminium-aluminium oxide (Al-Al_2O_3) graded composite structure was processed using 0%, 5%, 10% and 15% (from first layer to fourth layer) aluminium oxide as ceramic con- centration. A cylindrical steel die was used for the fabrication process of the FGM green compact. The green compact was prepared by applying cold pressing technique using a hydraulic press. The sintering process was imple- mented at 600 °C sintering temperature and 3 h sintering time using 2-step cycle. Microstructural characterization of the sample was conducted layer by layer using high resolution optical microscopy (OM). Hardness of the sample was also performed layer by layer using Vickers microhardness tester. The obtained results revealed that there is a uniform ceramic particle distribution within the metallic phase. From the microstructural observation it was clear that smooth transition occurred from one layer to next layer and each interface was distinct. It was also observed that there is a steady increase in layer hardness with the increase in ceramic concentration.

Keywords: Microstructure · Hardness · Aluminum · Aluminium oxide

1 Introduction

For diverse engineering applications, new generation engineering material known as functionally graded material (FGM) possesses multifunctional characteristics in one component. Within FGM, each composition gradually changes from one side to other side along thickness direction. For desired properties, FGM can be processed by combining the properties of metal and ceramic. For preparation of these graded materials, different processing methods, such as powder metallurgy, thermal spraying, vapor deposition,

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centrifugal casting etc. were followed by researchers [1–3]. Powder metallurgy is a method to achieve the desired properties and sintering is an important process to produce homogeneous or inhomogeneous structure free of defects [4–6]. Different combinations of graded composite materials were investigated theoretically and experimentally [7–10]. The properties of these composite structures were markedly influenced by sintering parameters, material composition, layer number, applied load, sintering environment etc. Multi-layered Graded composite materials were prepared by the application of laser melting deposition method and it was reported that there is strong bonding between substrate and deposited material [11]. Graded composite panels prepared by aluminum/high-density polyethylene were analysed theoretically and experimentally [12]. It was concluded that experimental results were agreed well with theoretical pre- dictions. Characteristics of aluminium based composite systems were analyzed and it was revealed that hardness of outer parts of composites is more than that of inner parts or middle parts [13]. Moreover, strength of outer region was greater than strength of inner region. Al/SiC graded composite material was manufactured by centrifugal casting method and the characteristics such as, microstructure, hardness etc. were analyzed [14]. Experimental results showed that properties of the composites were varied by applied load, sliding speed etc. Six-layered nickel-alumina functionally graded composite structure was prepared by pressureless sintering and microstructural observation con- firmed that gradation of composite took place from first layer to sixth layer [15].

In this study, graded composite specimen of aluminium-aluminium oxide (Al- Al_2O_3) was prepared considering 0%, 5%, 10% and 15% ceramic concentration. The graded composite structure was prepared through powder metallurgy method and 2- step sintering cycle. The properties such as microstructure and hardness were examined layer by layer.

2 Experimental

Four-layered Al-Al_2O_3 graded composite specimen was prepared considering 0%, 5%, 10% and 15% ceramic (Al_2O_3) concentration and through powder metallurgy method. In the fabrication process, three major steps were involved such as, mixing/blending of powders, compacting and sintering of specimen. At first stage, based on molecular weight of aluminium and aluminium oxide powders, the constituent of two materials for each layer composition was measured. After that, by allowing sufficient time, the constituents of two powder materials for each layer were sieved, mixed and blended in order to achieve good homogeneous mixture for each layer. During powder stacking process, the composition of powder was made in the order from 85%Al+15%Al_2O_3, 90%Al+10%Al_2O_3, 95%Al+5%Al_2O_3 and 100%Al+0%Al_2O_3 at the end of a cylin- drical steel die (diameter 30 mm) made of alloy steel. The cold compaction of speci- men was carried out by applying 30 ton (294.3 kN) uniaxial load manually using a hydraulic press. After application of loading, sufficient time was allowed so that the specimen (green compact) became at the stage of stable condition. Then, the specimen was carefully ejected from the die so that no wear or tear of specimen surface occurred. At this stage, the green compact was very fragile and had low cohesive strength. The graded composite specimen was sintered by a sintering furnace using a two-step sintering profile. The sintering process was carried out at 600 °C sintering temperature and 3 h sintering time. The sintered specimen was prepared for microstructural study. Characterization of specimen was performed layer by layer using metallurgical microscope. Finally, hardness of the sample was measured using a Vickers micro- hardness tester. Hardness measurements were carried out layer by layer for a dwell time 15 s using 300 gf (2.94 N) loading. Along the longitudinal axis (thickness direction) of the specimen, average hardness of 10 readings (within each layer) was considered as hardness value for each layer.

3 Results and Discussion

The microstructure of four-layered $Al\text{-}Al_2O_3$ graded composite specimen was exam- ined using a high resolution optical microscope. Characterization of sintered specimen was carried out for each metal-ceramic graded layer to determine whether ceramic particle distribution within the metallic phase is uniform or not. At first step, the sintered specimen was cut along the longitudinal direction and then it was mounted by cold mounting process. After grinding and polishing of the mounted specimen, microstructural observations were carried out and the resulting micrographs/images for all layers are presented in Fig. 1(a)–(d).

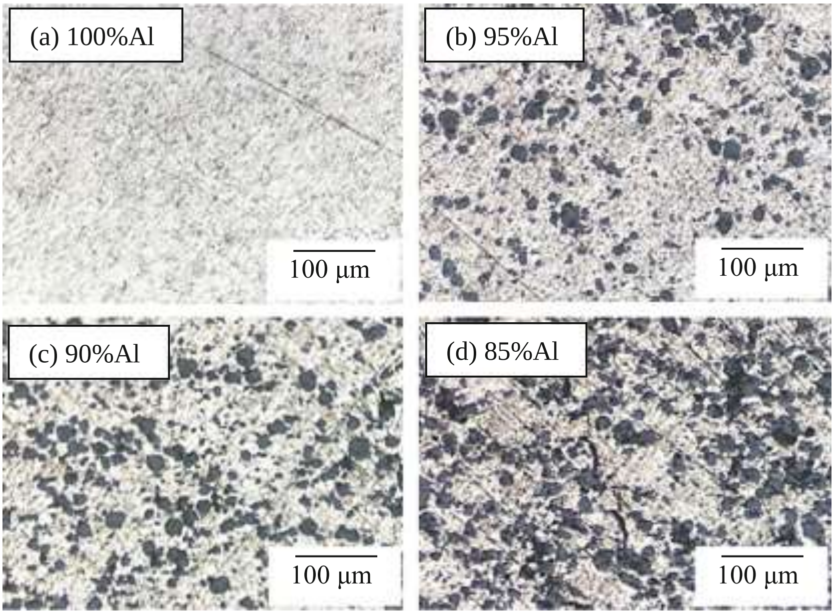

Fig. 1. Microstructures of $Al\text{-}Al_2O_3$ graded composite layers (a) 100% Al - 1st layer (b) 95%Al +5%Al_2O_3 - 2nd layer (c) 90%Al+10%Al_2O_3-3rd layer and (d) 85%Al+15%Al_2O_3-4th layer.

The microstructure of Fig. 1(a) consists only pure Al for first layer whereas, Fig. 1 (b), (c) and (d) consist of 95%Al+5%Al_2O_3, 90%Al+10%Al_2O_3 and 85%Al+15% Al_2O_3 for second, third and fourth layers respectively. It was noticed that the lighter phase is Al matrix and the darker phase is Al_2O_3. From these micrographs, it is distinctly evident that there is almost uniform dispersion of Al_2O_3 particles within Al matrix for second, third and fourth layers. It is also apparent that Al_2O_3 ceramic percentage is increased from second layer until fourth layer (5% to 15%).

Figure 2(a)–(c) show the interfaces for first-second layer, second-third layer and third-fourth layer by AA′, BB′ and CC′ respectively. In relation to these interfaces, no cracking was observed in between the layers or across any interface means that good powder stacking process, good preparation of each layer, good compaction process and good metal-ceramic bonding. It can also be observed that within graded structure, there is continuous and graded microstructure across each interface of adjacent two layers, as reported in previous investigation [8]. Moreover, it is distinctly evident that all inter- faces are nearly straight and parallel to each other which establish that in order to prepare the graded composite specimen, all processes were well implemented.

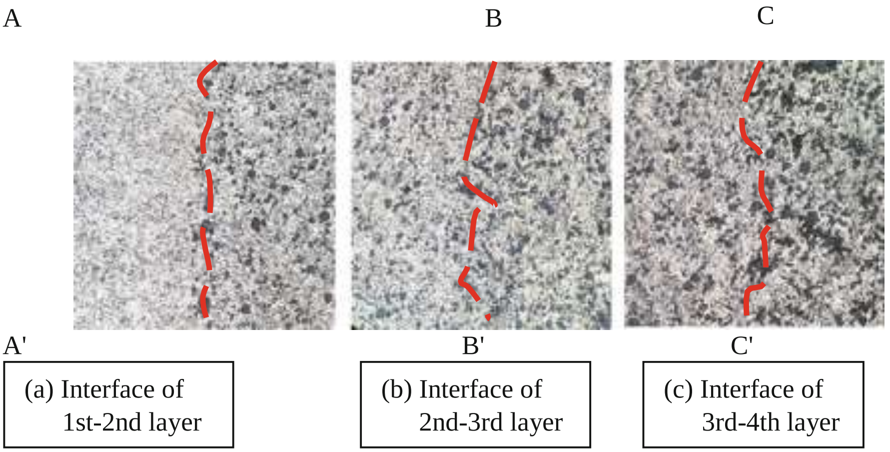

Fig. 2. Four layered Al-Al_2O_3 graded composite: Micrographs of interface: (a) 1st-2nd layer interface (AA′) (b) 2nd-3rd layer interface (BB′) (c) 3rd-4th layer interface (CC′).

Figure 3 shows the hardness variation for each layer and test results revealed that average hardness of first layer (100%Al) was 31.54 HV. From the indentation results, average hardnesses of second, third and fourth layers were measured as 32.08 HV, 32.52 HV and 32.94 HV. It is very clear that hardness value is steadily increased at each layer when the ceramics content is increased at the corresponding layer. These obtained results are well agreed with the results obtained by previous investigation [8]. The increment of hardness for each layer was reasonably consistent as aluminium oxide particles were well dispersed within aluminium matrix. Furthermore, it is distinctly evident that hardness increases layer by layer of the graded structure very consistently.

It is convinced that because of high hardness of ceramic particles and good interfacial bonding between metal and ceramic particles, continuous improvement in hardness occurred along the gradient direction of composite specimen [11, 16].

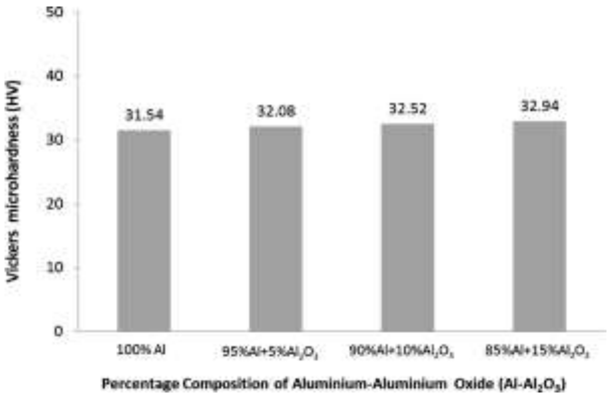

Fig. 3. Hardness variation in each layer of four-layered $Al-Al_2O_3$ graded composite structure.

4 Conclusions

Four-layered aluminium-aluminium oxide graded composite structure was prepared considering 0%, 5%, 10% and 15% ceramic concentration. Microstructural observa- tions revealed that there is uniform dispersion of ceramic particles within the matrix for second, third and fourth layers of the graded composite structure. No cracking was observed in between the layers or across any interface. Results also show that there is continuous and gradient microstructure across each interface of adjacent two layers. It is understood that all interfaces are nearly straight and parallel to each other. It is believed that preparation processes of graded composite structure were well imple- mented. Moreover, experimental data show that there is continuous improvement in hardness along the gradient direction of the composite structure.

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References

1. Khoddami, A.M., Sabour, A., Hadavi, S.M.M.: Microstructure formation in thermally- sprayed duplex and functionally graded NiCrAlY/Yttria-stabilized zirconia coatings. Surf. Coat. Technol. 201, 6019–6024 (2007)
2. Watanabe, Y., Hattori, Y., Sato, H.: Distribution of microstructure and cooling rate in Al- Al_2Cu functionally graded materials fabricated by a centrifugal method. J. Mater. Process. Technol. 221, 197–204 (2015)

3. Wu, K., Scheler, S., Park, H.S., Porada, M.W.: Pressureless sintering of ZrO_2-$ZrSiO_4$/NiCr functionally graded materials with a shrinkage matching process. J. Eur. Ceram. Soc. 33, 1111–1121 (2013)
4. Sun, L., Sneller, A., Kwon, P.: Fabrication of alumina/zirconia functionally graded material: From optimization of processing parameters to phenomenological constitutive model. Mater. Sci. Eng., A 488, 31–38 (2008)
5. Nuruzzaman, D.M., Kamaruzaman, F.F.B.: Processing and mechanical properties of aluminium-silicon carbide metal matrix composites. In: IOP Conference Series: Materials Science and Engineering, vol. 114, pp. 1–7 (2016)
6. Shahrjerdi, A., Mustapha, F., Bayat, M., Sapuan, S.M., Majid, D.L.A.: Fabrication of functionally graded hydroxyapatite-titanium by applying optimal sintering procedure and powder metallurgy. Int. J. Phys. Sci. 6, 2258–2267 (2011)
7. Tahvilian, L., Fang, Z.Z.: An investigation on thermal residual stresses in a cylindrical functionally graded WC-Co component. Mater. Sci. Eng., A 557, 106–112 (2012)
8. Erdemir, F., Canakci, A., Varol, T.: Microstructural characterization and mechanical properties of functionally graded Al2024/SiC composites prepared by powder metallurgy techniques. Trans. Nonferrous Met. Soc. China 25, 3569–3577 (2015)
9. Jamaludin, S.N.S., Basri, S., Hussain, A., Al-Othmany, D.S., Mustapha, F., Nuruzzaman, D. M.: Three-dimensional finite element modeling of thermomechanical problems in function- ally graded hydroxyapatite/titanium plate. Math. Probl. Eng. 2014, 1–20 (2014)
10. Jamaludin, S.N.S., Basri, S., Mustapha, F., Nuruzzaman, D.M., Latiff, M.I.A., Ismail, N.M.: Phase contamination characterization of stepwise-built functionally graded hydroxyapatite/titanium (HA/Ti) sintered under various atmospheres. Mater. Sci. Forum 889, 90–95 (2017)
11. Zhang, C.H., Zhang, H., Wu, C.L., Zhang, S., Sun, Z.L., Dong, S.Y.: Multi-layer functional graded stainless steel fabricated by laser melting deposition. Vacuum 141, 181–187 (2017)
12. Lin, Q., Chen, F., Yin, H.: Experimental and theoretical investigation of the thermo- mechanical deformation of a functionally graded panel. Eng. Struct. 138, 17–26 (2017)
13. Radhika, N., Raghu, R.: Development of functionally graded aluminium composites using centrifugal casting and influence of reinforcements on mechanical and wear properties. Trans. Nonferrous Met. Soc. China 26, 905–916 (2016)
14. Prabhu, T.R.: Processing and properties evaluation of functionally continuous graded 7075 Al alloy/SiC composites. Arch. Civil Mech. Eng. 17, 20–31 (2017)
15. Latiff, M.I.A., Nuruzzaman, D.M., Basri, S., Ismail, N.M., Jamaludin, S.N.S., Kamaruza- man, F.F.: Preparation and characterization of 6-layered functionally graded nickel-alumina (Ni-Al2O3) composites. In: IOP Conference Series: Materials Science and Engineering, vol. 342, pp. 1–8 (2018)
16. Kamaruzaman, F.F, Nuruzzaman, D.M., Ismail, N.M., Hamedon, Z., Iqbal, A.K.M.A., Azhari, A.: Microstructure and properties of aluminium-aluminium oxide graded composite materials. IOP Conference Series: Materials Science and Engineering, vol. 319, pp. 1–6 (2018)