Wear Characteristics of Functionally Graded Tubes Reinforced with Silicon Carbide and Alumina: A Comparative Study

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Abstract: In the current study, an effort has been taken to manufacture and compare the characteristics of functionally graded tubes. Two samples have been produced with a commercially pure aluminium matrix reinforced by 10%(in weight) SiC and Al_2O_3 with a 16 μm average size via horizontal centrifugal casting. In addition to microstructure analysis, the mechanical and wear characteristics have been investigated across the thickness of the produced tubes. The results showed that the addition of SiC and Al_2O_3 particles relative to the unreinforced matrix (pure Al) significantly enhance the mechanical properties and wear resistance of the produced tubes. Thus, these tubes are the best choice for automobile applications.

Key words: functionally graded materials; centrifugal casting; pure aluminium; wear characteristics

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0 Introduction

With the advancement of technology at an increasing pace, the need for advanced materials with conflict properties in many applications becomes essential[1]. This necessity is also evident in other ways in which engineers investigate the uses of these newly designed materials[2-3], because day after day, the progress of materials increases their characteristics, and restricted use cannot be handled to attain the properties required for particular applications for usable materials, such as pure metals and alloys or conventional composites[4].

To solve this problem, researchers in Japan have developed functionally graded materials (FGMs). FGMs are an advanced type of conventional composite materials where compositions or microstructures differ gradually, thereby creating a particular improvement in the material properties in a specific direction[5]. In recent years, FGMs have been very significant for researchers in many areas, including automotive, aerospace, biomaterials, electronics, and others, due to their unique graded material characteristics[6]. FGMs are useful where one end of the layer needs to withstand severe conditions and where the other side of the substrate must be attached to the base material that requires protection against these harsh environments. Over the last years, the production techniques of FGMs have been developed, as there are now several techniques used to manufacture these graded materials, such as centrifugal force methods, powder metallurgy methods, vapour deposition methods, thermal spray methods, slip casting methods, and additive manufacturing methods[7]. In particular, centrifugal casting and powder metallurgy techniques have proved useful in the production of FGMs with smooth variation in microstructures and/or compositions. Centrifugal casting is usually more appealing

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to the FGMs production by creating significantly greater parts than those produced from powder metallurgy. Besides, centrifugal casting methods with numerous benefits produce a continuous gradient and cost-efficient method for producing FGMs compared to other methods[8]. Aluminium alloys are extensively used in the manufacture of FGMs and have entered the industrial stage of development among the different matrix materials available. Also, various ceramic particles, such as SiC, B_4C, Al_2O_3, Zircon, and TiC, have been used to reinforce Al alloy for producing graded composites. Rao et al.[9] produced functionally graded Al6061 reinforced with 10% (in weihgt) of B_4C particles via a centrifugal casting method. They studied the effect of mould speed on microstructure behaviour and mechanical characteristics. Their findings show that the particle concentration in the outer zone increases with the increased mould rotational speed. Consequently, the outer zone properties were significantly improved at a higher mould speed. In another relevant study, Junus and Zulfia[10] produced functionally graded Al6061- Al_2O_3 composites with different weight fractions of particles via the centrifugal casting method. Their results show that the hardness of graded composites increases as the weight fractions of the particle increases from the inner to the outer zone. Saleh and Ahmed[11] developed and evaluated the mechanical properties and wear performance of functionally graded Al-Al_2O_3 tubes through a centrifugal casting process. Their results showed that the hardness and tensile stress in the outer region improved by 34% and 17%, respectively, compared to the inner region of the produced tubes. Recently, Fathi et al.[12] prepared functionally graded AZ91-SiC tubes with different weight fractions of particles via the centrifugal casting method. They studied the effect of material parameters on the microstructure behaviour, mechanical properties, and wear performance. Their findings exhibit that the mechanical properties and wear resistance of graded tubes increase as the weight fractions of particles increase from the inner to the outer zone. The above review indicates that only a limited number of data are available on the influence of pure Al reinforced with SiC and Al_2O_3 particles on mechanical and wear performance for FGMs. Hence, the principal aim of this study is to produce and compare functionally graded tubes based on pure Al reinforced with SiC and Al_2O_3 particles via centrifugal casting in order to evaluate the mechanical and wear characteristics.

1 Materials and Methods

1.1 Materials and fabrication method

In the present study, the experiments were carried out using commercially pure aluminium as a matrix to manufacture graded tubes via a centrifugal casting method. Also, pure aluminium gives economic consideration to the cost of producing graded tubes relative to Al alloys. The graded tubes were strengthened by 10% (in weihght) of Al_2O_3 and SiC particles with an average size of 16 μm due to their distinct properties, such as high hardness and wear resistance. In contrast to commercially pure aluminium with a density of 2 700 kg/m^3, the Al_2O_3 and SiC particles have a density of 3 690 and 3 200 kg/m^3, respectively. The properties of used particles have terribly high hardness and high wear resistance; thus, adding ceramic particles to the pure Al matrix can significantly improve mechanical properties and wear performance. The centrifugal casting process was used to fabricate graded tubes (with 230 mm outer diameter and 12 mm thickness) at a mold rotational speed of 1 000 r/min. The matrix material was melted in a graphite crucible at 725 ℃, while the used particles were simultaneously heated to 250 ℃. The dried particles were added to the molten metal and stirred at 150 r/min for 10 min before pouring into the machine feeder tube. The centrifugal casting machine used in the experiments is shown with more details in a previous publication[8].

1.2 Tests and analysis techniques

In order to check the distribution of particles across the graded thickness of the produced tubes, the specimens were cut with dimensions of 20 mm × 20 mm × 2 mm using a wire electrical discharge machine. The initial polishing was done in grits 320, 600, 800, 1 200, and 1 500, respectively, by using emery papers. The final polishing was carried out with 0.05 μm liquid alumina to create a mirror surface, followed by 0.5% diluted hydrofluoric acid for 15 s used as an etchant to display boundaries. The Olympus BX51 M optical microscope was used to observe the microstructure. A scanning electron microscope with a field emission (SEM, Sirion 200) was used to monitor worn surfaces. The Image J program was used to evaluate and measure the concentration of particles gradient from outside to inside zones of graded tubes.

The MRB-250 was used as a hardness testing machine for a 62.5 N load and a 5 mm steel ball indenter. The machine measured the Brinell hardness values by catching the indentation dimensions created by the steel ball indenter. The average of five hardness values was measured in order to obtain a consistent average value. In compliance with the ASTM E8 Standard, the tensile test samples were cut and prepared from the graded tubes. A universal testing machine (Model: UTM4294X) was used to conduct tensile testing on the graded tubes in separate zones (outer, middle, and inner) to track reinforcement particle distribution. Tensile testing was carried out with a strain rate of 5×10^{-4} s^{-1} at room temperature.

The dry sliding wear tests were conducted at room temperature using a ball on disk type machine based on ASTM: G99 standard. The specimens with dimensions of 10 mm × 10 mm × 2 mm were used in order to examine the wear rate for graded tubes at various zones. All tests were conducted with a constant sliding speed of 200 r/min and a sliding time of 5 min under varying load conditions 10—50 N.

2 Results and Discussion

2.1 Microstructure evaluation

Fig.1 shows the panorama view of microstructures from the outer surface to the inner surface for SiC and Al_2O_3 particles across the thickness of the graded tubes. The graded thickness of the tube can be divided into three zones, which are outer, middle, and inner zones, depending on the particle distribution in the pure Al. The particle distribution usually relies on a variety of factors, including rotational speed, the density differential between matrix and particles, the cooling rate, and the molten metal viscosity. As the Al_2O_3 density (3 690 kg/m^3) is higher than SiC particles (3 200 kg/m^3), the filling width of the particles is smaller because it has a large centrifugal force, as shown in Fig. 1. The panorama view also reveals the heterogeneous distribution of particles in the pure Al, and thus, the mechanical characteristics and wear performance can be controlled through the graded distribution.

Fig.2 shows the microstructures of the graded tubes in the outer zone, which ensures that the segregation of the Al_2O_3 and SiC particles occurs under the action of the centrifugal force. The higher density particles move towards the outside surface of the graded tube during a centrifugal casting process, while lighter particles fall within the rotating axis. This is mainly because of the centrifugal force controlling the movement of particles and molten metal; the high density causes ceramic particles to push away from the rotating axis and to form the outer zone that is enriched with particles.

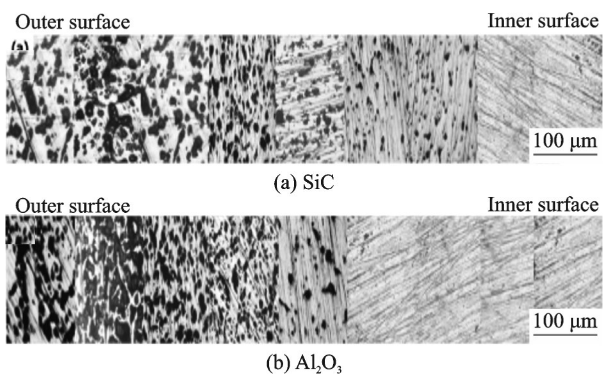

Fig.1 Panoramic view of the microstructures of tubes along the radial direction reinforced by SiC and Al_2O_3

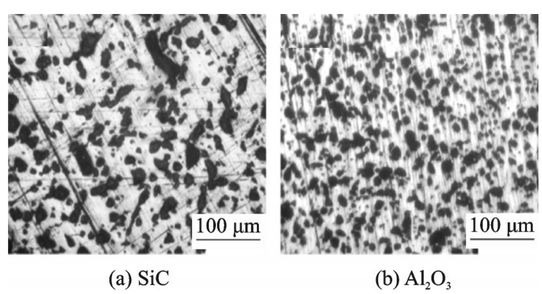

Fig.2 The microstructure of graded tubes at outer zone reinforced with SiC and Al_2O_3

2.2 Particles Evaluation

Fig.3 shows the concentration of particles strengthened by 10% (in weight) of particles across the graded thickness of the tube. Particles gather in the outer zone to reach a higher concentration, and then the concentration of particles decreases through a smooth gradation across the tube thickness. For Al_2O_3 and SiC reinforced tubes, the maximum concentration of particles obtained in the outer zone was 48% and 39%, respectively. Also, the reduction in the concentration rate of the Al_2O_3 particles is considerably higher than that of the SiC particles, mainly because of the centrifugal force generated from the difference in density of the particles used to manufacture the graded tubes. Besides, the gradient of particles (distribution) across SiC-reinforced graded tubes is smoother than Al_2O_3 particles, as seen in Fig.3. Moreover, the gradient of the particle concentration can be used to evaluate the properties' percentage improvement across the thickness of the produced tubes. Finally, the particle analysis findings explicitly show that the gradient characteristics of the manufactured tubes can be controlled through the density variation between pure Al matrix and hard particles.

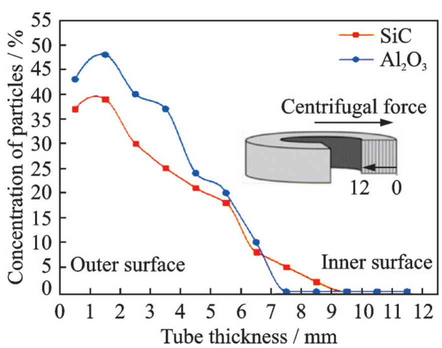

Fig.3 Concentration of particles through thickness

2.3 Mechanical properties evaluation

Fig.4 displays the variation of Brinell hardness values of the graded tubes from the outer to the inner surface across the graded thickness. Also, Fig.4 shows that the Brinell hardness value of the graded tubes reinforced with Al_2O_3 and SiC particles is higher than the hardness value of the used matrix (pure Al 25 BHN). Although the tube reinforced by Al_2O_3 particles has a higher concentration of particles on the exterior surface, the hardness value of the tube reinforced with SiC becomes higher at the outer surface due to the Al_2O_3 particles clumped on the outer surface, which leads to weakening the matrix. Nevertheless, the improvement in the hardness value of the middle zone is not increasing with the same rate attained in the outer zone. In comparison, there was no change in the Brinell hardness value in the inner zone relative to the values described for the pure Al matrix due to the lack of particles in this zone. At the outer zone, the calculated Brinell hardness values were 47.2 and 49.3 Brinell hardness number (BHN) for the produced tubes reinforced with Al_2O_3 and SiC, respectively; while in the middle zone, the determined Brinell hardness values were 32.3 and 31.3 BHN for the tubes reinforced with Al_2O_3 and SiC, respectively, as shown in Fig.4.

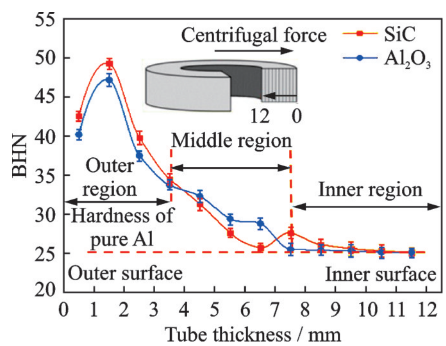

Fig.4 Hardness for the graded tubes across thickness

Fig.5 indicates the ultimate tensile strength values of the graded tubes reinforced with Al_2O_3 and SiC particles at different three zones (outer, middle, and inner zones). Although a graded tube reinforced with 10% (in weight) of Al_2O_3 particles has

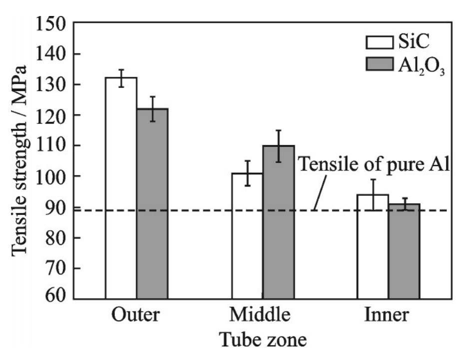

Fig.5 Tensile strength for the graded tubes at different zones

the maximum concentration of particles in the outer region, according to Fig.3, it does not have the highest tensile strength on the outer region of the gradient tube. This is mainly because the aggregation of particles in the outer region has resulted in the degradation of the pure Al matrix. However, there was a more considerable improvement in the graded tube reinforced with Al_2O_3 in the middle zone than the tube reinforced with SiC particles, as shown in Fig.5. This was primarily due to the better distribution of Al_2O_3 particles in this region (no particle agglomeration). At the outer zone, the measured tensile strength values were 122 and 132 MPa for the produced tubes reinforced with Al_2O_3 and SiC, respectively; while in the middle zone, the obtained tensile strength values were 110 and 101 MPa for the produced tubes reinforced with Al_2O_3 and SiC, respectively.

2. 4 Wear evaluation

Fig.6 demonstrates the variation of the wear rate values versus the type of particles for the different zones (outer, middle, and inner) of the graded tube. Typically, the wear rate values of the graded tubes increase with the increase of the radial distance from the outside surface to the inner surface. The inner zone of the graded tube shows a higher rate of wear, while the outer and middle zones display a lower rate of wear regardless of the reinforcement type, as seen in Fig.6. Also, the graded tube reinforced with SiC particles has the lowest wear rate at the outer region, while the Al_2O_3 reinforced tube has the lowest wear rate in the middle region among the produced tubes. The main explanation is because of the particle aggregation in the case of

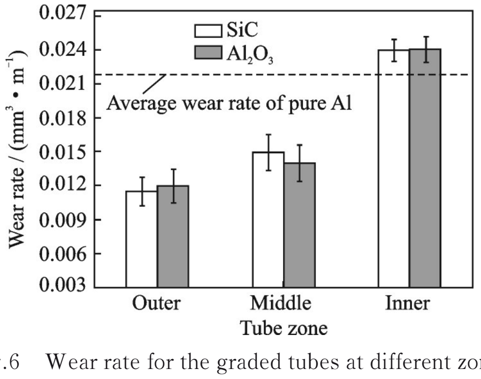

Fig.6 Wear rate for the graded tubes at different zones

Al_2O_3 on the outer surface of the tube (Fig.1), resulting in a weakening of the matrix and therefore in a reduced hardness and wear resistance for graded tubes. For tubes reinforced with SiC particles, the obtained wear rate values were 0.011 57, 0.014 97, and 0.023 96 mm^3/m for the outer, the middle, and the inner zones, respectively. In comparison, the wear rate values in the case of tube reinforced by Al_2O_3 particles were 0.011 98, 0.014 03, and 0.024 12 mm^3/m for the outer, the middle, and the inner zones, respectively. This result is presented in our previous research[11].

Fig.7 displays the SEM pictures of worn surfaces in the different zones (outer, middle, and inner) of the graded tubes. The outer zone has a better wear resistance than other zones. It has small grooves and less degradation, as seen in Fig.7(a). This is mostly due to the existence of the highest content of particles in this zone. When the surface distance towards the inner surface of the tube increases, the concentration of particles declines inside the pure Al and thereby increasing the wear rate, thus changing the wear mechanism from moderate to extreme wear, as seen in Fig.7(b,c).

In general, the presence of particles within the pure Al matrix contributed to a significant improve-

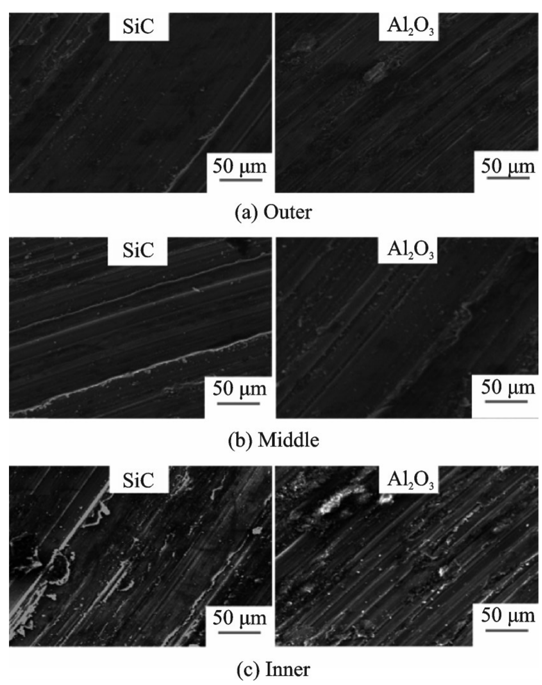

Fig.7 SEM images for the worn surface of the tubes at different zones of outer, middle, and inner

ment in the wear resistance of graded tubes. Fig.8 shows the effect of applied load on variations of wear rate values (at outer zone) of the graded tubes produced with various SiC and Al_2O_3 particles. It can be indicated that the wear resistance reduces for all the graded tubes tested with increasing applied loads, as shown in Fig.8. For tubes reinforced with SiC particles, the obtained wear rate values were 0.006 94, 0.011 57, and 0.01674 mm^3/m for the 10, 30, and 50 N, respectively. In comparison, the wear rate values in the case of tube reinforced by Al_2O_3 particles were 0.007 52, 0.011 98, and 0.017 61 mm^3/m for the 10, 30, and 50 N, respectively. Fig.9 shows SEM images of worn surfaces for the graded tubes at various applied loads under constant wear conditions of 200 r/min and 5 min. The images indicate that the grooves increased considerably as the applied load was raised. Also, the friction and build-up of wear debris between the sample and disk are mainly responsible for decreasing the wear resistance with the increased applied load. As seen in Fig.9(a), the pin surface at a low load is mostly exposed with sliding fine and shallow grooves. The wear resistance decreases because of elevated contacting pressure with rising applied load. Also, the higher applied load (50 N) exposes deep grooves and ploughing around the entire worn surface, as seen in Fig.9(b).

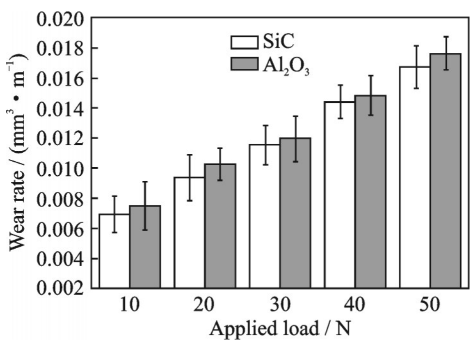

Fig.8 Wear rate for the graded tubes at different loads

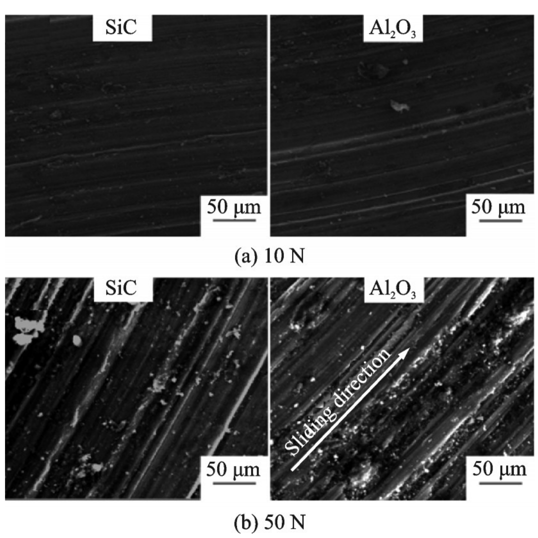

Fig.9 SEM images for worn surface of the tubes at different loads of 10 and 50 N

3 Conclusions

In this research, the functionally graded pure Al tubes reinforced by SiC and Al_2O_3 particles were manufactured successfully through the centrifugal casting method. In the microstructural analysis, a maximum concentration of particles has been achieved at the outer and middle zones of the produced tubes; thereby, the mechanical and wear characteristics have been enhanced compared to the inner zone. In the case of a tube reinforced with SiC particles, the properties on the outer zone improved considerably, while the middle layer was enhanced significantly in the graded tube strengthened with Al_2O_3 particles. It can be noticed from the SEM images that the surface integrity and quality of the SiC reinforced specimens are much better than the Al_2O_3 reinforced specimens, whether at the outer, middle, and inner zones or different loading conditions. In particular, the tubes produced in this study have outstanding mechanical and wear characteristics and are ideal for applications that are demanding high mechanical characteristics and wear resistance at the surface region.

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Author contributions Dr. **SALEH Bassiouny Ibrahim** designed the study, performed the experiments, conducted the analysis, interpreted the results, and wrote the manuscript. Prof. **AHMED Mahmoud Hamed** contributed to the discussion and background of the study, revised and modified the manuscript. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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碳化硅和氧化铝增强功能梯度管磨损性能的比较研究

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摘要: 本研究致力于制造和比较功能梯度管的特性。采用水平离心铸造的方法,用平均尺寸为 16 μm,质量分数为 10% 的 SiC 和 Al_2O_3 增强的商用纯铝基体制备出两个样品。除了微观结构分析外,本文还研究了梯度管整体厚度区间的机械和磨损特性。结果表明,相对于未添加增强基体(纯铝)的材料之外 SiC 和 Al_2O_3 增强颗粒的加入显著提高了管材的力学性能和耐磨性。颗粒增强管材是作为汽车应用的最佳选择。

关键词: 功能梯度材料;离心铸造;纯铝;磨损性能