This research is an experimental comparison study to show the influence of mold type casting on mechanical properties. The study considers the aluminum alloy of a gasoline engine piston with nanoparticles alumina Al_2O_3 size 25 nm manufactured in two types of molds. Sand mold and cast-iron mold were selected to cast the aluminum composite components. A systematic comparative study of tensile strength and hardness properties of cast aluminum components is made on sand and metal molds production. The nano powder can add to enhance the mechanical properties must not exceed 4 % for metal and sand mold casting. According to data for hardness, adding nano alumina powder has minimal impact on metal mold casting, but it significantly improves sand casting. From a financial standpoint, metal casting provides higher economic values for making piston aluminum castings. The hardness rises as the alumina content does in two molds as compared to the obtained specimen. It demonstrates that the highest hardness occurs at 4 % alumina in the sand-casting mold and at 6 % alumina in the metal. When the compositions of the casting materials are the same, a comparison of the fracture morphology between sand and mold casting reveals more ductile fractures for metal molds compared to brittle fractures in sand cast by large silicon separation grains because of higher grain growth in sand casting by longer solidification time. The same is seen in mold casting, which exhibits reduced ductility due to the alumina nanoparticles' dispersion strengthening process in the aluminum matrix. This arises as a result of nano alumina dispersion acting as barriers to dislocation motions in the aluminum matrix, enhancing strength but reducing ductility

Keywords: casting-mold, mechanical-properties, piston-alloy, alumina, sand-casting, powder, ductile, fracture, hardness, grain

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INFLUENCE OF THE MOLD TYPE ON THE MECHANICAL PROPERTIES OF THE PISTON ALLOY WITH NANO ALUMINA IN CASTING AND METAL MOLD

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1. Introduction

The piston is generally made up of cast iron. Revolutionary changes in piston manufacturing using Al-Si alloys give greater efficiency with less material cost [1, 2]. Sand casting is a traditional metal forming method and a vital necessary process in the foundry sector, the products widely utilized in automotive, aerospace, machine tool components, and other industries [3, 4]. Nanoparticles have been added to the aluminum alloys in different sizes and amount to accomplish specific properties for services duty. Throughout the shaped casting process, the residual stress was studied concerning mold restrictions and cooling rate [5]. Aluminum casting problems with two nondestructive testing methodologies are used to investigate when the pouring rate varies, and penetrant and ultrasonic tests were performed to describe the surface [6].

A thorough understanding of the failure mechanisms of aluminum matrix composites will broaden our understanding of the behavior of these advanced materials under applied tensile loads. Therefore, studies that are devoted into the influence of manufacturing factors and material specifications on the tensile and fracture behavior of composites has become are scientific relevance.

2. Literature review and problem statement

The paper [7] presented the effect of the addition of nanoparticles to the matrix alloy on the mechanical properties used stir casting method. The experimental findings supported the effectiveness of the powder metallurgy approach for producing friction materials as well as the potential to increase brake pad friction coefficient. While in paper [8], used vortex casting method to reinforced 7075-T6 aluminum alloy by adding SiC particle. The distribution of nanoparticles in the base was visualized using field emission scanning electron microscopy pictures, and it was discovered that the size of the nanoparticles in the base is less than 100 nanometers. Milling and hot pressing used in [9] to produce nanoparticle titanium carbide (TiCNP) reinforced AA7075 alloy. Tensile tests revealed that the ultimate tensile strength (284.46 MPa) of the 1 hour milled TiCNP/AA7075 composite was 40 percent higher than that of the original AA7075 alloy (210.24 MPa). The ultimate strength and the elongation are enhanced with the addition of Nano-clay-particles in [10] and with the heat treatment of cylinder-head aluminum alloys to improve the mechanical properties of the base material. Results showed that the reinforcing had caused the aluminum alloy's microstructure to become finer. The effect of heat treatment on the fatigue and toughness behavior of CK45 steels was studied by [11], as well as a study of various heat treatments on the microstructure and micro-hardness across the depth of the specimens. The findings showed that compared to other examples, the water quenched steel alloy recorded a greater curve component. The yield stress and the ultimate tensile strength of micro-tensile test specimens increase when decreasing the mold temperature from 1,000 to 700 °C for different specimens was cast using an aluminum bronze by [12]. The results of the experiment demonstrated that, because micro-specimens have a finer microstructure that restricts dislocation movement, their mechanical strength is higher than that of macro-specimens cast at the same mold temperature. The compo-casting method was used by [13] to fabricate aluminum matrix composite reinforced with micro alumina particles, improvement in hardness, compression strength, and impact energy obtained due to using compo casting. The mechanical results demonstrated an increase in yield strength, ultimate tensile strength, compression strength, and hardness due to the inclusion of alumina (micro and nano). Stir casting process with vacuum to reduce the porosity was used by [14] in the fabrication of Aluminum alloy A356, however the study limited to use B4C material. As the weight percentage of B4C particles in the AMCs increased, the mechanical parameters such as tensile strength, hardness, and porosity improved while the impact strength and percentage elongation declined. [15] discovered that increasing the mixing time of nanocomposite material components could result in an increase in their thermal conductivity. It was demonstrated that the qualitative relationship between the density of nanocomposites and the time taken for their components to mix is qualitatively similar to the relationship between those two variables for their thermal conductivity. The study limited to specific time used. The hardness and tensile strength properties of composite alloys improved by [16] with the inclusion of alumina nanoparticles. The experiment's findings indicated that adding alumina nanoparticles improved the composite alloy's hardness and tensile strength before the weight ratio reached 6 %, the research used restrictive size nanoparticle in all experiments. Wear improved by [17] using hybrid nanoparticle additive to the aluminum alloy. As the proportion of hybrid Nano-reinforced materials is increased, the produced composites' hardness (BH) rises. To better understand the failure mechanism of the castings under various loading conditions, the fracture surface of each specimen was examined by [18] with a scanning electronic microscope.

The specimens' fracture surfaces are created as cracks spread along grain boundaries. An SEM fractograph at low magnification makes this obvious.

In the middle range, the failure modes transition. In addition, [19] examined the crystal structure and the morphology. Furthermore, even though the sodium titanate phase was seen to be present in the structure, X-Ray diffraction study of the nanotube crystal structure revealed that post-hydrothermal treatment increased the crystallinity of the anatase TiO_2 phase. Based on the literature, there were unresolved issues the different effects of mold casting and sand casting on the mechanical properties of the composite material. A way to overcome these difficulties, based on our knowledge, no one has tested the material of piston with additive Al_2O_3 size 25 nm in specific weight percent to explore the changes in mechanical properties considering metal and sand molds. All this suggests that, it is advisable to conduct a study on Piston alloy- Al_2O_3 composites containing 0 to 6 % percentage of Al_2O_3 in step 5 have produced by the stir casting process and study the effect of Al_2O_3 particles on mechanical properties in two different casting methods to study the differences in the mechanical properties.

3. The aim and objectives of the study

The aim of the study is to show the influence of the mold type on the mechanical properties of the piston alloy with Nano alumina particles of size 25 nm.

To achieve this aim, the following objectives are accomplished:

– to make tensile test;

– to examine hardness;

– to make scanning electron microscopy and energy dispersive spectroscopy.

4. Materials and methods

4. 1. Sand casting procedure

Dry yellow sand was used as core sand in which the sand was cleaned and sifted from impurities. The bonding material of sodium silicate Na_2Sio_3 was added with a specific amount to the sand grains to obtain cohesion and strength. The sand molding was placed inside the heating oven at a temperature of 200 °C for two hours to obtain cohesive sand. The chemical analysis for the scrap of piston shown in Table 1. The scrap melted in the furnace up to 620 °C for 15 min and then stir the mixture with an electric mixture prepared for this purpose as in Fig. 1–3.

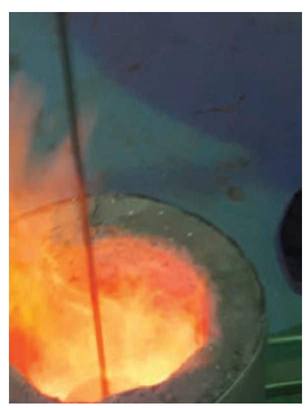
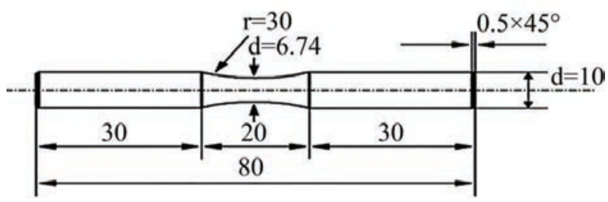


Fig. 1. Material in the furnace

Fig. 2. Pouring in the sand casting



a *b*

Fig. 3. Sample with dimensions: *a* – product sample; *b* – dimensions of the specimen

Table 1

Chemical analysis for melted scrab piston heads

Element	*w*, %
Si	11.8
Fe	0.596
Cu	1.29
Mn	0.305
Mg	1.13
Zn	0.335
Cr	0.0325
Ni	0.744
Ti	0.157
Pb	0.0173
P	0.07
V	0.02
Others	0.0176
Al	Rem.

The alumina material is added to the melting pot and stirred in the mixture for 5 min to ensure a homogenous texture. The last step is pouring the mixture into the sand-casting mold as in Fig. 2. After solidification, the samples must be prepared for testing as in Fig. 3, *a*, *b*.

4. 3. Mold casting procedure

Mold casting is done simply by preparing a steel block mold with two-part joined by rivets where every part represents half of the mold and the inner side lubricated.

4. 4. Experimental tests

Tensile Test. Eight tensile samples were prepared considering the dimensions of a diameter of 10 mm and a length of 100 mm shown in Fig. 3 for the two molds. Four samples in sand casting and four samples in metal mold casting. The first sample from each mold was the base composite alloy as received with no additional materials, the second sample included 2 percent alumina nanoparticles in the composite, and the third sample included 4 % alumina nanoparticles in the composite. The fourth sample was made up of a 6 percent alumina Nanoparticles composite. The tensile test was performed using an Instron tensile test machine using the ASTM E8 standard at a pull speed of 10 mm.

Hardness Examination. The hardness of the received and other composite materials alloys was evaluated using Vickers hardness testing equipment with a force of 60 kgf. Eight samples are prepared for the hardness test. Four sample of metal casting and the other four of sand casting. SEM and EDS tests.

SEM and EDS tests were done using (EBSD Instrument: ZEISS SIGMA VP/Germany). The test was done with respect to the fractured surface to examine microstructural features and micro-chemical analysis for the tested points.

5. Results of the comparison of mechanical properties for the two mold castings

5. 1. Tensile Test

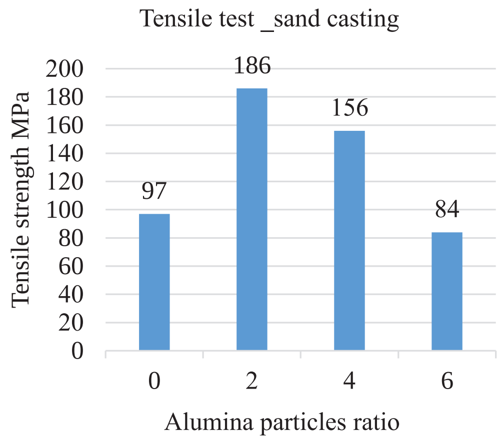
The result for tensile strength is listed in Table 2 for the eight specimens produced in metal and sand casting. The compared results are shown in Fig. 3. It shows that the maximum tensile strength occurs at 2 % of alumina additive to the base matrix in the metal mold while in a sand mold. In both molds the tensile strength decreases when the alumina additive reaches 6 %.

Generally, metal mold casting gives better tensile results with an average value of 166 MPa for metal mold casting and 131 MPa for sand casting with increasing of 26 % in metal mold cast.

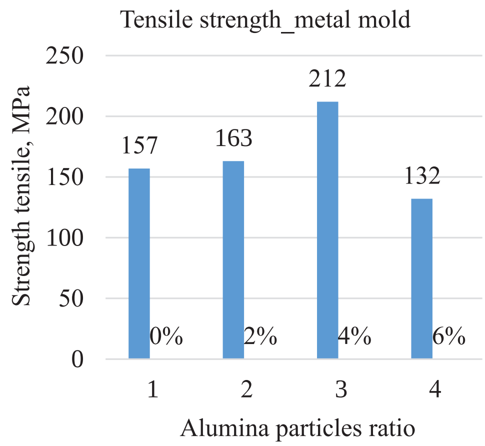
Table 2

Tensile strength of master alloy and composite

Mold type	The values of tensile strength of master alloy and composite with addition alumina			
	As received Alloy 0 %	2 % Al_2O_3	4 % Al_2O_3	6 % Al_2O_3
Metal mold	157 MPa	163 MPa	212 MPa	132 MPa
Sand mold	97 MPa	186 MPa	156 MPa	84 MPa

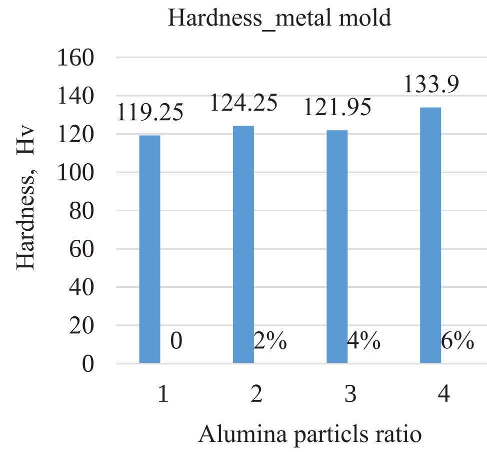


a



b

Fig. 4. Tensile strength properties of received alloy and composite materials: *a* – tensile for sand casting; *b* – tensile test for mold casting



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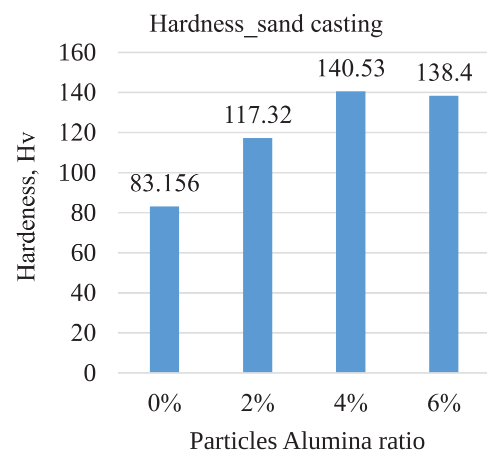


b

Fig. 5. Hardness results test of received alloy and composite materials: *a* – hardness in sand casting; *b* – hardness in metal casting

5. 2. Hardness Examination

Hardness is needed as an indication of wear resistance during service of piston part. Table 3 listed the conducted results of the hardness for each mold. Three reading for each case of nanoparticles additive. The average of the readings and the standard deviation gives the same indication of comparisons. Fig. 5 shows the hardness results in metal and sand-casting molds. In metal mold casting alumina nanoparticles percentage has little effect on the cast hardness and variation between lowest and highest values of about 11 %. The average hardness value is 124.24 HV. In sand casting the effect of alumina adding is remarkable where the variation of resulted hardness is about 68 % from 83 for cast without additive to 140.53 for 4 % of Alumina addition. However, the average hardness for sand casting is 119 HV less than metal casting at 11 %.

Table 3

Hardness test of master alloy and composite

No. Exp.	Al_2O_3 ratio	First reading HV		Second reading HV		Third reading HV		Average reading HV		Standard deviation	
		Sand	Metal	Sand	Metal	Sand	Metal	Sand	Metal	Sand	Metal
1	0 %	87.11	116.3	61.36	122.2	101	119.25	83.156	119.25	39.815	53.371
2	2 %	94.57	129.1	141.2	119.4	116.2	124.25	117.32	124.25	54.993	55.663
3	4 %	121.0	123.4	141.2	120.4	159.4	122.05	140.53	121.95	64.281	54.530
4	6 %	129.6	131.2	166.2	136.6	119.4	133.9	138.4	133.9	64.268	59.885

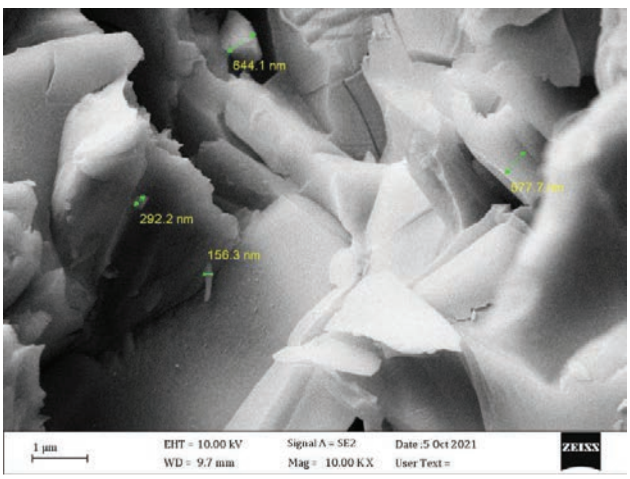
It shows the maximum hardness occurs when the alumina is 4 % in sand casting mold and is maximum in metal at 6 % alumina.

5. 3. Results of Scanning Electron Microscopy and Energy Dispersive Spectroscopy tests

Fig. 6 represents Scanning Electron Microscopy SEM fractured surface for 2 % alumina additive to the matrix. In part (a) concerning sand casting and part (b) concerning metal mold casting. In Fig. 6, *a* the fracture feature is cleavage brittle mechanism by separating crystalized silicon grains while aluminum matrix separated by shear mechanism. Fig. 6, *b* shows mixed fractures. The morphology and chemical analysis for fractured by tensile test metal mold as received cast specimen shown in Fig. 7 has as indicated by Energy Dispersive Spectroscopy (EDS) tests chart high silicon and another element higher than what founded in chemical analysis for alloy. The EDS test was used to identify where the fracture happened accurately. In Fig. 8 the fracture was mixed (brittle-ductile) with 2 % alumina. In Fig. 9 with higher Nano alumina powder content (4 %) the fracture is more complex. Large rectangular aluminum grain failed with less ductility and higher magnification. With increasing alumina content to 6 % in Fig. 10 EDS analysis shows more aluminum surface and less silicon fractured surface.

In sand casting, the composite (as received), low tensile strength belongs to high ductility of the fractured surface shown in Fig. 11 with high dimples percentage appear in alloy and EDS shows higher aluminum content approving that. By adding 2 % of alumina nano powder to sand casting cast as in Fig. 12 there are grain enlargement and higher aluminum content in EDS analysis. Strengthening mechanism by desperation is the main cause of tensile strength improvement but with adding more alumina as shown in Fig. 13 the tensile strength lowered as discussed in Fig. 10. Adding 6 % of nano alumina powder to sand casting cast shows complex fine fracture morphology as in Fig. 14 where most of the alumina particles hinder grain growth and agglomerated on grain boundaries lowering strength with fine grins fracture features.

Comparing fracture morphology between sand and mold casting with the same compositions shown in Fig. 15, more ductile fracture for metal mold to a brittle fracture in sand cast by large silicon separation grains due to higher grain growth in sand casting by longer solidification time. The same is seen in Fig. 16–18.



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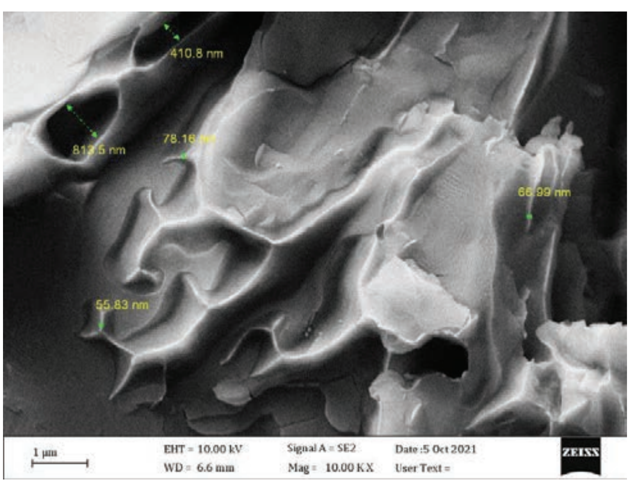
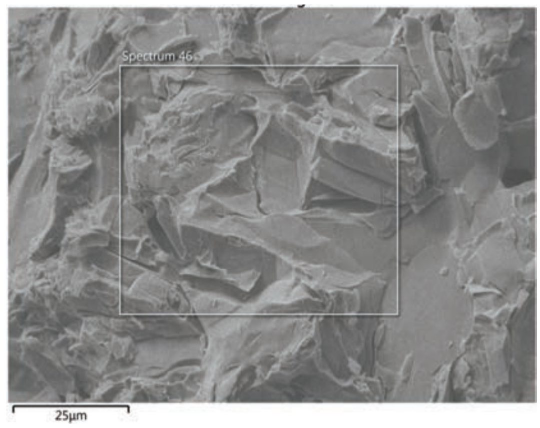


b

Fig. 6. Field Emission Scanning Electron Microscopy Morphology for fracture section: *a* — 2 % Alumina by sand casting; *b* — 2 % Alumina by Metal mold casting



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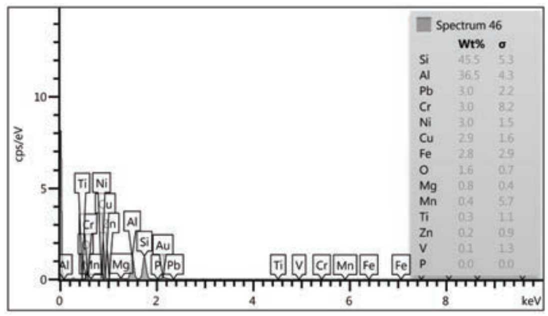
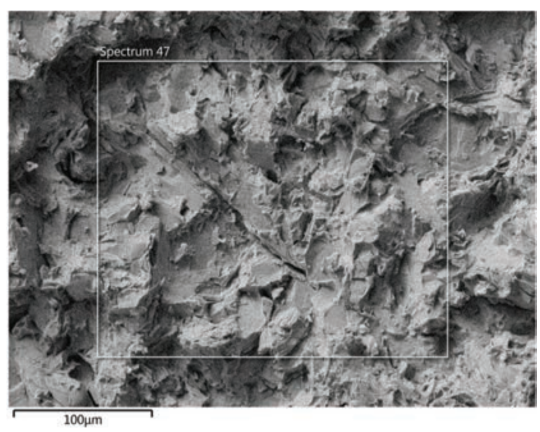


b

Fig. 7. Field Emission Scanning Electron Microscopy Morphology and Energy Dispersive Spectroscopy samples: *a* — 0 % Alumina by metal casting; *b* — 0 % Alumina by metal with chemical analysis



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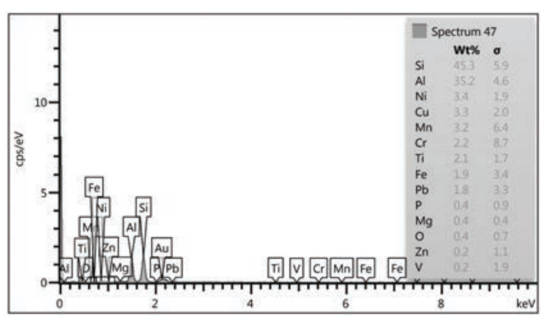
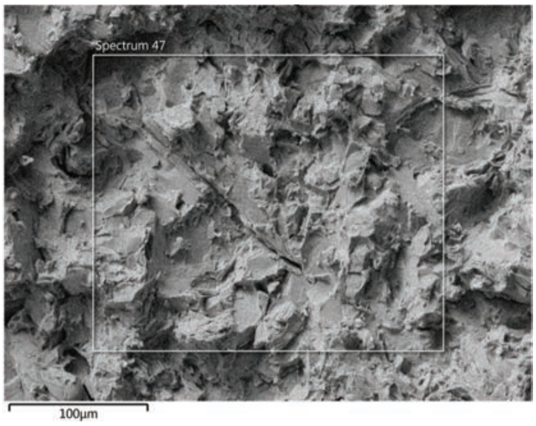


b

Fig. 8. Field Emission Scanning Electron Microscopy Morphology and Energy Dispersive Spectroscopy samples: *a* — 2 % Alumina by metal casting; *b* — 2 % Alumina by metal with chemical analysis



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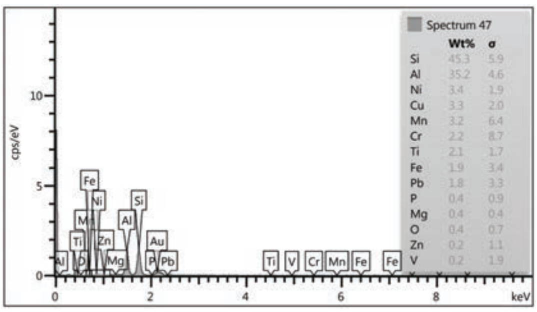

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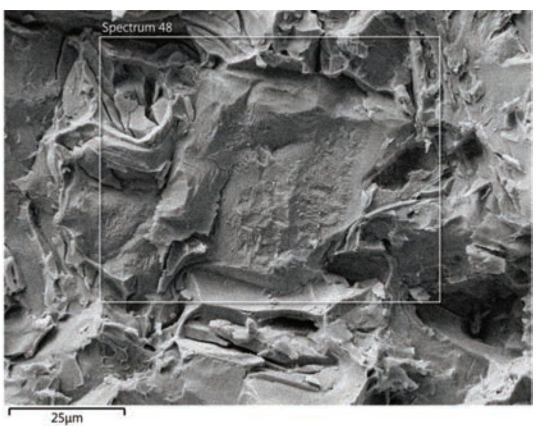
Fig. 8. Field Emission Scanning Electron Microscopy Morphology and Energy Dispersive Spectroscopy samples: *a* – 2 % Alumina by metal casting; *b* – 2 % Alumina by metal with chemical analysis



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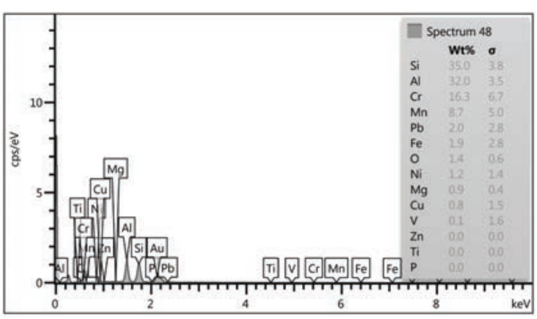
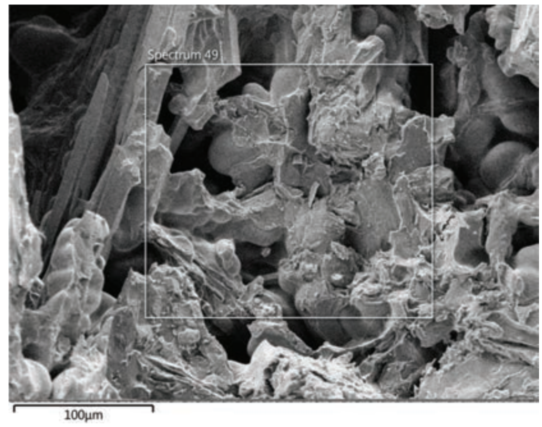


b

Fig. 9. Field Emission Scanning Electron Microscopy Morphology and Energy Dispersive Spectroscopy samples: *a* – 4 % Alumina by metal casting; *b* – 4 % Alumina by metal with chemical analysis



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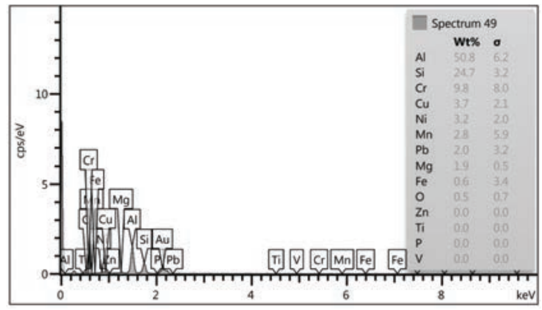
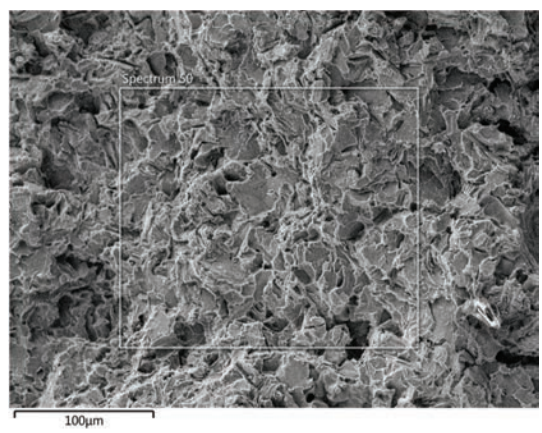


b

Fig. 10. Field Emission Scanning Electron Microscopy Morphology and Energy Dispersive Spectroscopy samples: *a* – 6 % Alumina by metal casting; *b* – 6 % Alumina by metal with chemical analysis



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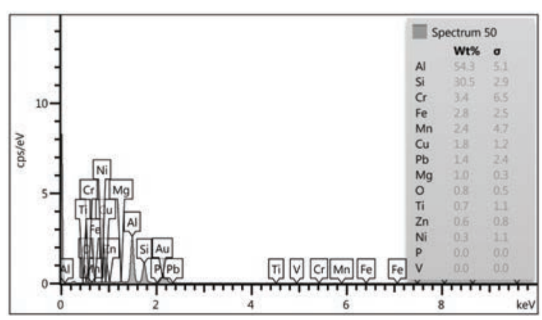
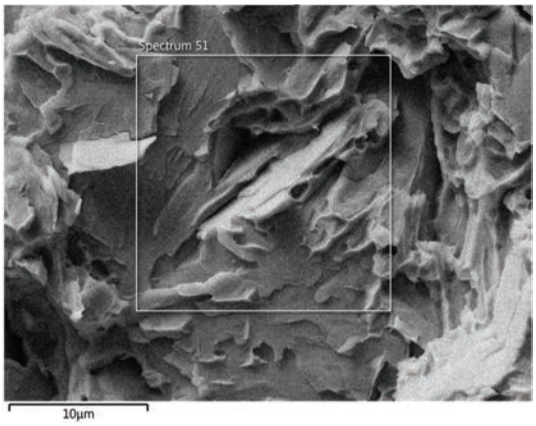


b

Fig. 11. Field Emission Scanning Electron Microscopy Morophology and Energy Dispersive Spectroscopy samples: *a* – 0 % Alumina by sand casting; *b* – 0 % Alumina by sand casting with chemical analysis



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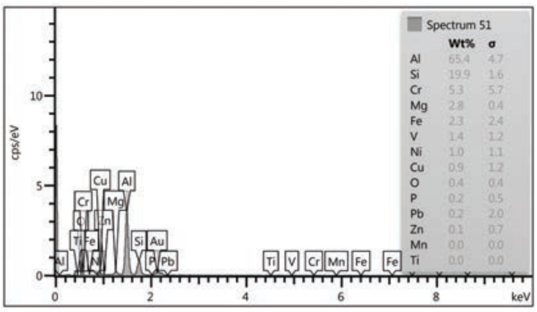
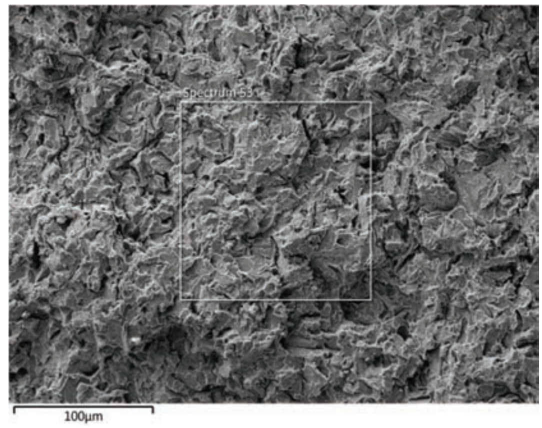


b

Fig. 12. Field Emission Scanning Electron Microscopy Morphology and Energy Dispersive Spectroscopy samples: *a* — 2 % Alumina by sand casting; *b* — 2 % Alumina by sand casting with chemical analysis



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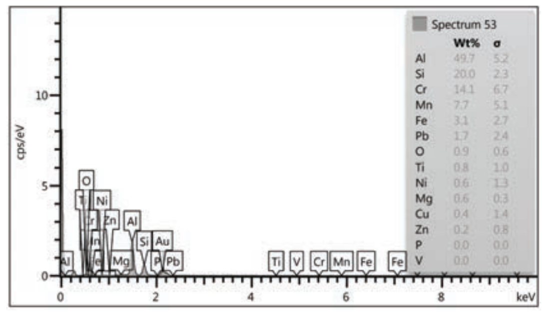
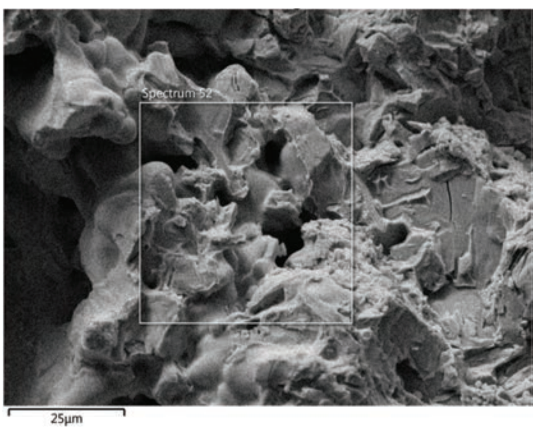


b

Fig. 14. Field Emission Scanning Electron Microscopy Morphology and Energy Dispersive Spectroscopy samples: *a* — 6 % Alumina by sand casting; *b* — 6 % Alumina by sand casting with chemical analysis



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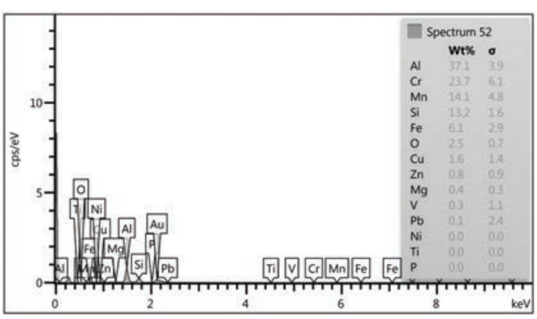
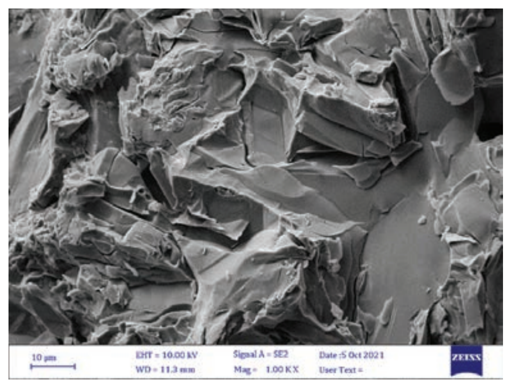


b

Fig. 13. Field Emission Scanning Electron Microscopy Morphology and Energy Dispersive Spectroscopy samples: *a* — 4 % Alumina by sand casting; *b* — 4 % Alumina by sand casting with chemical analysis



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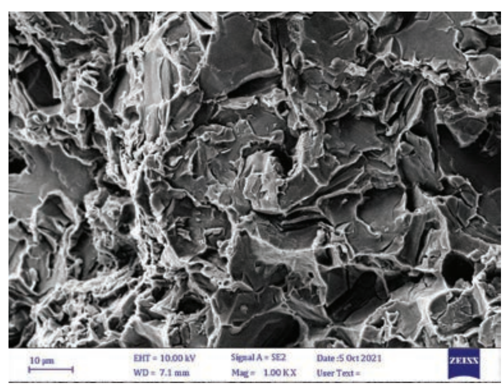
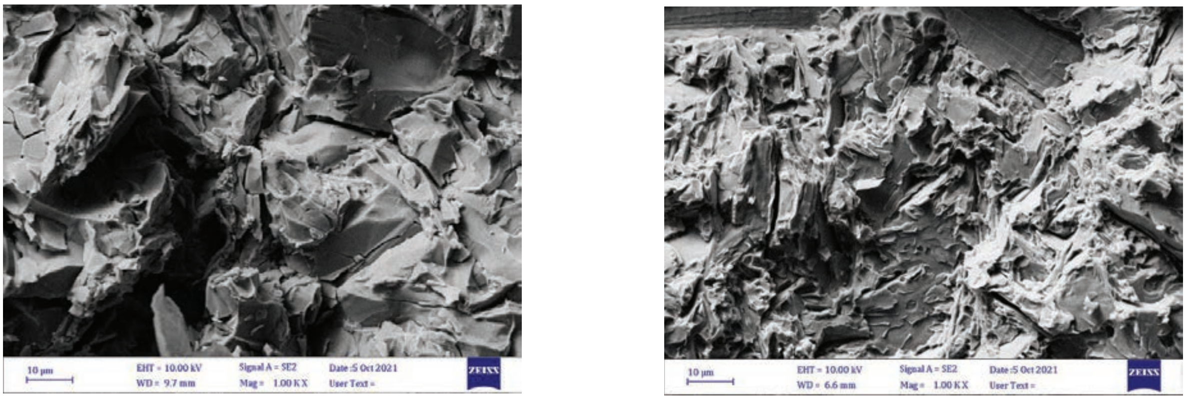


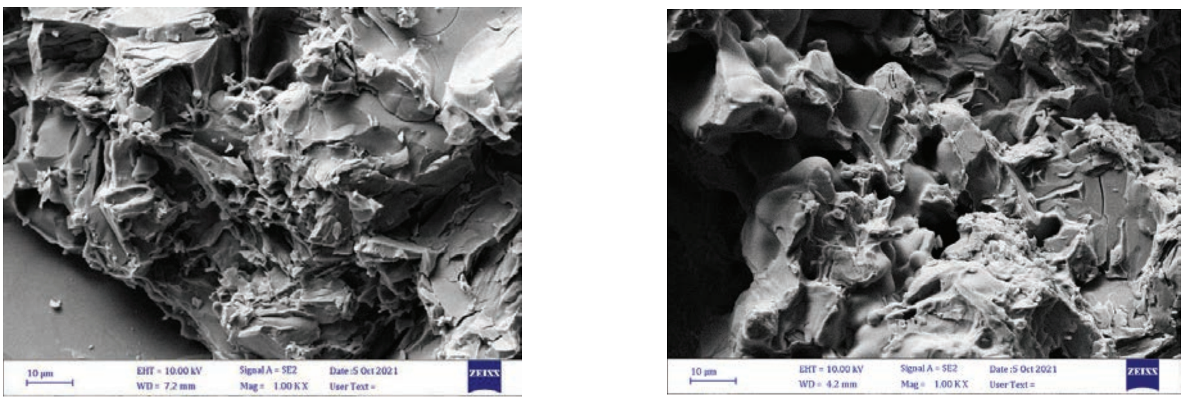
b

Fig. 15. Field Emission Scanning Electron Microscopy Morphology for fracture section: *a* — as received sand casting; *b* — as received metal mold casting



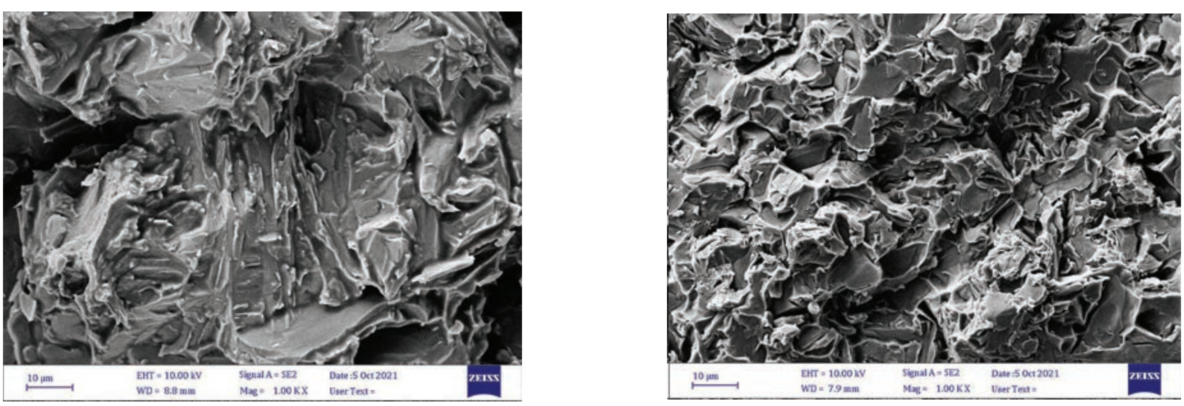
a *b*

Fig. 16. Field Emission Scanning Electron Microscopy Morphology for fracture section: *a* – 2 % alumina sand casting; *b* – 2 % alumina metal mold casting



a *b*

Fig. 17. Field Emission Scanning Electron Microscopy Morphology for fracture section: *a* – 4 % alumina sand casting; *b* – 4 % alumina metal mold casting



a *b*

Fig. 18. Field Emission Scanning Electron Microscopy FESEM Morphology for fracture section: *a* – 6 % alumina sand casting; *b* – 6 % alumina metal mold casting

By contrast, the fracture is initiated by the debonding of the interface between the matrix and large particles if compression is dominant. Cracks are developed between primary voids due to void sheeting, which gives rise to relatively smooth fracture surfaces.

6. Discussions of experimental results of mechanical prosperities with the two mold casting

In this work, an experimental comparison study was implemented for metal and sand mold casting to show the influences of the mold type casting on the mechanical properties of a composite material with different amounts of alumina nanoparticles.

The maximum amount of alumina Nano powder that may be used to improve the mechanical qualities must not exceed 4 %, the maximum tensile strength happens with 4 % of alumina as seen in Fig. 4. It is due to the nonhomogeneous of the material in both casting. It agrees with the reference [13]. According to data for hardness, adding Nano alumina powder has minimal impact on metal mold casting, but it significantly improves sand casting, there is a huge improvement for powder addition as seen in Fig. 5, and from a cost perspective, metal casting gives better economic values for producing piston aluminum casts. In comparison to the received specimen in two molds the hardness increases as the alumina increase. The hardness rises as the alumina content does in two molds as compared to the obtained specimen. It demonstrates that the highest hardness occurs at 4 % alumina in the sand-casting mold and at 6 % alumina in the metal.

When the compositions of the casting materials are the same, a comparison of the fracture morphology between sand and mold casting reveals more ductile fractures for metal molds compared to brittle fractures in sand cast by large silicon separation grains because of higher grain growth in sand casting by longer solidification time. The fracture appears with fine striations about one micrometer between each one. This appears because nano alumina dispersion in aluminum matrix working as obstacles to dislocation movements causes increased strength and decreased ductility as seen in Fig. 9.

So, when there is high silicon content indicates the fracture happened across silicon grains and when the other elements appear in high concentration indicates the fracture happened in intermetallic compound grains. The same is seen in mold casting, which exhibits reduced ductility due to the alumina nanoparticles' dispersion strengthening process in the aluminum matrix. This arises as a result of nano alumina dispersion acting as barriers to dislocation motions in the aluminum matrix, enhancing strength but reducing ductility. The overall structure is uncompleted dendritic with many separations between grains due to high content of alumina powder leading to stopping junction between grains because of their low affinity with aluminum matrix or other structural features. This caused less tensile strength as it was 132 MPa dropped from 212 MPa with 4 % of alumina content.

Using a scanning electron microscope, the specimens' fracture surfaces are analyzed. The cleavage mechanism causes the initial breakage in the tensile testing at the big silicon particles. Cracks that form along grain boundaries cause the round bars to completely fail. A few dimples can be seen on the fracture surfaces. If compression is the dominating force, on the other hand, the fracture is started by the debonding of the interface between the matrix and big particles. Vacuum sheeting, which creates relatively smooth fracture surfaces and causes cracks to form between major voids.

The limitations of the study are: the homogeneity of the solution in the stir-casting method when using the electric handle string. The time used for stirring is another parameter of limitation. From the knowledge of previous studies increasing time in a limited range makes the construction of the additive particle more homogeneous, however, increasing the time makes the electric motor damaged because of extensive heat from the string of the solution. Beside, cannot increase the nanoparticle amount since the alloy will lose the ductility properties. The stirrer speed should be taken into consideration in the study.

7. Conclusions

1. Maximum alumina nano powder can add to enhance the mechanical properties must not exceed 4 **%** for metal and sand mold casting.

2. From hardness results, adding nano alumina powder have little effect on metal mold casting but in sand casting, there is a huge improvement for powder addition, and from a cost perspective, metal casting gives better economic values for producing piston aluminum casts. In comparison to the received specimen in two molds the hardness increases as the alumina increase. It shows the maximum hardness occurs when the alumina is 4 **%** in sand casting mold and is maximum in metal at 6 **%** alumina.

3. Comparing fracture morphology between sand and mold casting with the same compositions shows more ductile fracture for metal mold to a brittle fracture in sand cast by large silicon separation grains due to higher grain growth in sand casting by longer solidification time. The same is seen in mold casting showing less ductility by dispersion strengthening mechanism of the alumina nanoparticles in the aluminum matrix. This appears because of nano alumina dispersion in aluminum matrix working as obstacles to dislocation movements increasing strength but decreasing ductility.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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