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Stir casting studies on aluminium (Al8011) and zirconia (ZrO_2) metal matrix composites

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Abstract: This study investigates the properties of Aluminium (Al8011) and Zirconia (ZrO_2) metal matrix composites (MMCs) fabricated through stir casting, which is a common technique used to produce MMCs. Al8011 was used as the matrix material whilst ZrO_2, a ceramic material, was used as the reinforcement. The composites were developed with varying weight percentages of ZrO_2 (4, 8 and 12 wt%) and were analysed using tensile, wear and hardness, scanning electron microscopy (SEM) and hardness testing. The findings show that as the percentage of ZrO_2 increased in the composites, the density and hardness significantly increased. SEM results revealed that the distribution of ZrO_2 was homogenous throughout the matrix, indicating the method of stirring was effective in improving particle dispersion. Overall, the study concluded that MMCs with high percentage of ZrO_2 has the potential to enhance mechanical and physical properties whilst maintaining insignificant level of porosity. However, future research is needed to address the impurities identified in this study.

Keywords: Stir casting, Wear test, Tensile test, Hardness test, Scanning Electron Microscopy (SEM)

1. Introduction

The development of Metal Matrix Composites (MMCs) dates back to the early 1900s but gained significant attention in the 1960s when the aerospace industry began researching ways to reduce weight and increase strength in their components [1-2]. The early MMCs used tungsten and molybdenum as the reinforcing materials, but these were expensive, and their high density made the composites heavier than desired. In the 1980s, ceramics such as silicon carbide and aluminium oxide were explored for use as reinforcements in MMCs [3-6]. These ceramics offered high stiffness and hardness, which improved the mechanical properties of the composites. However, the high cost and difficulty in processing these ceramics limited their use, leading to the exploration of alternative ceramics such as zirconia [7].

Aluminium is widely used as the matrix material in MMCs due to its low density, good conductivity, and excellent corrosion resistance. However, on its own, it lacks mechanical strength, which limits its use in structural applications. To improve the mechanical properties of Al, ceramics, such as zirconia, are incorporated into the matrix using various fabrication techniques. Stir casting, a method for producing MMCs, was developed in the 1970s as a cost-effective and efficient way to manufacture composites [6, 8]. The technique involves stirring a molten matrix material while adding the reinforcement to create a uniform distribution of the reinforcement in the matrix. In recent years, research into the fabrication of MMCs using stir casting has gained significant attention due to its ability to produce composites with superior mechanical and physical properties. This study explores the use of stir casting in the development of Al8011-ZrO_2 metal matrix composites [9].

Metal Matrix Composites (MMCs) have been extensively researched in recent years due to their excellent mechanical and physical properties provided by the combination of two or more dissimilar materials [10-12]. Among the reinforcing materials used in MMCs are ceramics, which offer high hardness and tensile strength whilst reducing the weight of the composite. Aluminium (Al) is one of the most commonly used matrix materials due to its low density, high corrosion resistance and good conductivity. However, pure Al has low mechanical properties, hence the need for reinforcement. Zirconia (ZrO_2) has been recognized as one of the most suitable ceramic materials in improving the mechanical properties of Al. Stir casting is a widely accepted method for producing MMCs that involves stirring the molten matrix material whilst adding the reinforcement [13]. This study investigates the effects of various weight percentages of ZrO_2 on the mechanical and physical properties of Al8011-ZrO_2 composites fabricated through stir casting. The study aims to analyse the microstructure and composition of the composites to determine the potential of stir casting as a technique for developing high-performing MMCs.

2. Materials and procedures

Table 1. The weight percentage of reinforcement

Aluminum 8011	**Zirconium dioxide (ZrO_2)**
96	4
92	8
88	12

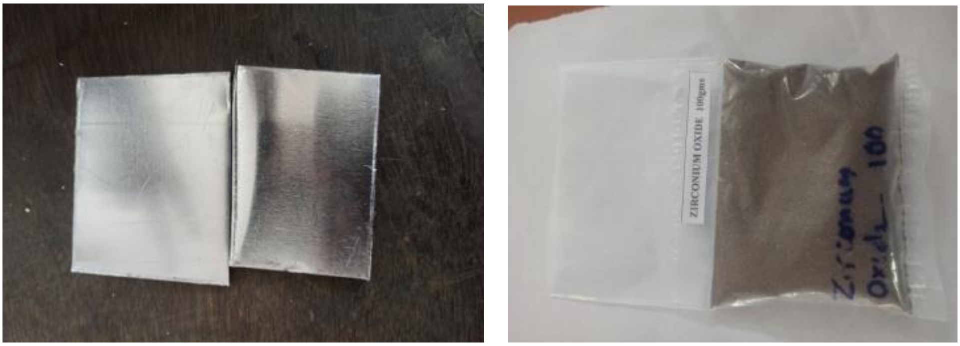


Figure 1. Al8011-Zirconium Oxide (ZrO_2)

2.1. Stir casting process

The stir casting process can be used to produce metal matrix composites (MMCs) using various metal matrices and reinforcement materials. In the case of Al8011 and zirconia, the process would involve the following steps.

2.1.1. Melting

The Al8011 alloy would be melted in a furnace or induction heating system, and the temperature would be monitored to ensure that it is completely molten.

2.1.2. Reinforcement addition

While the Al8011 is molten, the zirconia particles would be slowly added to the mixture. The zirconia particles being used are typically preheated before adding to the molten metal to prevent thermal shock.

2.1.3. Stirring

A mechanical stirrer would be used to uniformly distribute the zirconia particles throughout the molten Al8011 alloy. The stirring speed and time would be optimized to ensure that the zirconia particles are well dispersed throughout the alloy.

2.1.4. Casting

Once the stirring process is complete, the molten Al8011-zirconia composite would be poured into a mold to achieve the desired shape and size of the final product.

2.1.5. Solidification

The molten Al8011-zirconia composite would be left to solidify and cool down in the mold. Cooling rates would be controlled to obtain the desired properties.

2.1.6. Finishing

Once the composite has fully cooled, it would be removed from the mold and subjected to finishing processes such as grinding, polishing, or machining.

The resulting Al8011-zirconia composite would have improved mechanical and thermal properties over the base Al8011 alloy due to the presence of the zirconia reinforcement particles. The specific properties of the composite would depend on factors such as the percentage of zirconia added and the size and shape of the particles used.

Figure 2. Stir casting process

3. Results and discussion

3.1 Wear Test

The wear test is a critical process used to assess the performance of Al8011 and zirconia composites in real-world applications. The following steps can be used to conduct a wear test for Al8011 and zirconia composites.

3.1.1. Sample preparation

The Al8011 and zirconia composite materials are cut into specific shapes and sizes that are appropriate for the wear test. The surface of each material is then polished to a specified roughness to ensure uniformity.

3.1.2. Test rig setup

The sample is loaded onto the wear testing machine, which is set up to apply a controlled frictional force. The test conditions such as the load, speed, and duration are then set to mimic the working conditions that the composite material will undergo during its actual use.

3.1.3 Wear testing

The wear testing machine is started, and the sample is subjected to the required load and speed for the specified duration. During this time the wear of each sample is measured by recording the volume of material removed from the surface through an accurate measurement process.

3.1.4. Analysis

The amount of material removed is recorded and analysed to evaluate the performance of the Al8011 and zirconia composite against the standard material used in the application. The properties of the Al8011-zirconia composite material, such as the coefficient of friction, wear resistance, and hardness, are evaluated at various stages to establish the extent of wear.

3.1.5. Results

The results of the wear test are analysed to determine the performance of the composite material in terms of its wear resistance and suitability for the intended application. These results can be used to optimise the composite material and verify its suitability for the particular application. In conclusion, wear testing is a critical step in evaluating the performance of Al8011 and zirconia composites, and it assists in verifying their suitability in different manufacturing and engineering applications.

Figure 3. Wear test specimen

Table 2. Wear Test Results

Sample Number	Load (N)	Speed (RPM)	Time (Mins:Secs)	Height Loss Wear (µ)	Frictional Force (N)
1	20	386	4:10	38	10.8
	20	572	4:10	17	10.6
	20	760	4:10	20	10.3
2	20	386	4:10	80	8.7
	20	572	4:10	56	10.7
	20	760	4:10	65	10.4
3	20	386	4:10	40	7.6
	20	572	4:10	31	9.5
	20	760	4:10	42	10.7

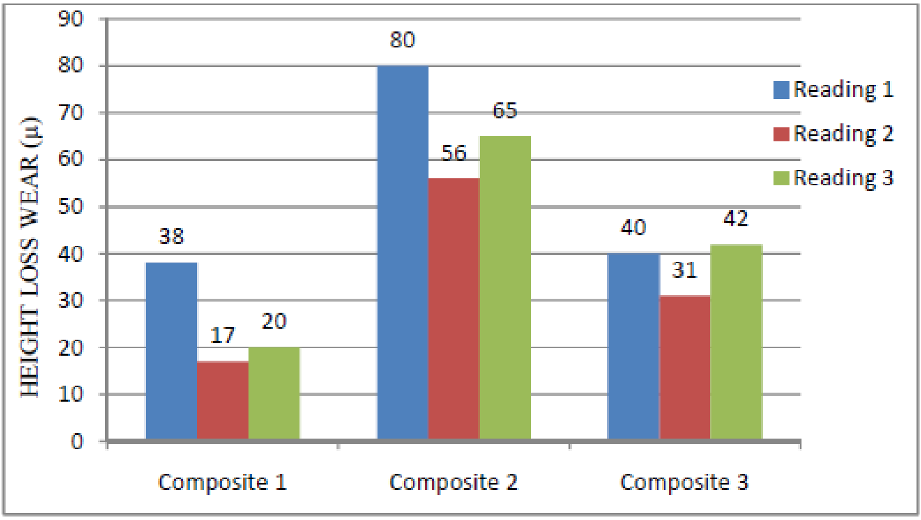


Figure 4. Comparison of three wear test results

From the above data, we can see that sample 2 has a much higher wear loss than the other two samples, sample 1 and sample 3. However the amount of friction is nearly the same for all samples. Yet the wear loss in sample 1 is minimal.

3.2. Tensile test

The tensile test can be performed to evaluate the mechanical properties of samples 1, 2 and 3 (Al8011-96%+ Zirconia -4%, Al8011-92%+ Zirconia 8% and Al8011-88%+ Zirconia -12%) to determine their suitability for different applications requiring high strength and fracture resistance. The following steps can be used to conduct the tensile test for these samples.

3.2.1. Sample preparation

The Al8011-zirconia composite materials are cut into specific shapes and sizes appropriate for the tensile test. The samples should be clean, free of any debris, burrs or cracks, and should be marked for easy identification.

3.2.2. Test rig setup

The samples are loaded onto the tensile testing machine, which is set up to apply a controlled force. The machine should be calibrated, and the samples should be placed in the centre of the grips, ensuring that the loading direction is aligned with the specimen axis.

3.2.3. Test conditions

Set the crosshead speed and strain rate of the tensile testing machine, and record the dimensions of the samples prior to testing, such as gauge length, diameter, or thickness. The test conditions should be the same for all samples to ensure consistency in the results.

3.2.4. Tensile testing

The machine is started, and the tensile force is applied to each sample. During this process, the deformation, load, stress, and strain are measured and recorded. The test will continue until the sample fractures completely.

3.2.5. Analysis

The data collected during the test is analysed to determine the mechanical properties of the Al8011-zirconia composite materials. From this data, the tensile strength, yield stress, elongation, modulus of elasticity or Young's modulus, and other desired mechanical properties can be calculated for each material.

3.2.6. Results

The results of the tensile test are analysed to evaluate the performance of the composite materials and to compare them with the results of previous tests or the performance of the standard material used in the application. The results can also be considered in light of the percentage of zirconia added to the aluminum to determine the ideal ratio for specific applications.

In conclusion, the tensile test can be used to evaluate the mechanical properties of samples 1, 2, and 3 Al8011-zirconia composite materials. The results can help to determine the suitability of these materials for different applications and help to guide further research and development to optimize the mechanical properties.

Figure 5. Samples before Tensile Test

Figure 6. Samples after tensile test

Table 3. Tensile test results

S. No	Composite	Yield load (kN)	Yield Stress (MPa)	Tensile Strength (MPa)
1	Composite 1	12.34	96.9	103.97
2	Composite 2	14.40	108.56	116.78
3	Composite 3	12.27	92	96.44

Knowing that Composite 2 has greater ultimate tensile strength than Composites 1 and 3 comes from the above table. Composite 2 has a better tensile strength than Composites 1 & 3 because Zirconia is evenly distributed throughout.

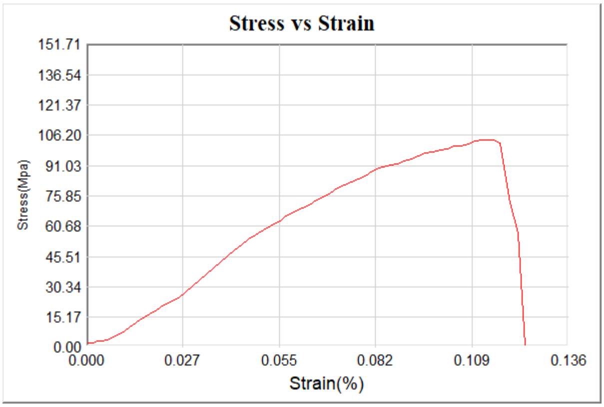


Figure 7. Stress Vs Strain curve for sample 1

The stress vs. strain curve for sample 1 is displayed in the graph above. When the stress rises, the strain follows suit until a stress of 103.97 Mpa is reached. The sample is elastically bent up to 103.97, at which point it breaks. The stress of the application is stopped.

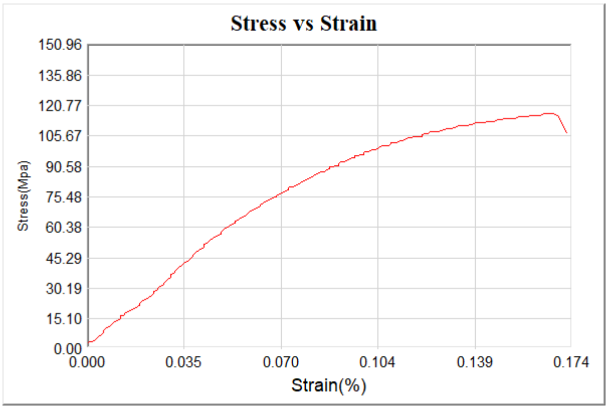


Figure 8. Stress Vs Strain curve for sample 2

The graph up above displays the sample 1 stress vs. strain curve. The strain gradually increases as the stress does until 116.78 Mpa of load is applied. Sample is shattered at 116.78 Mpa after being elastically deformed up to that point.

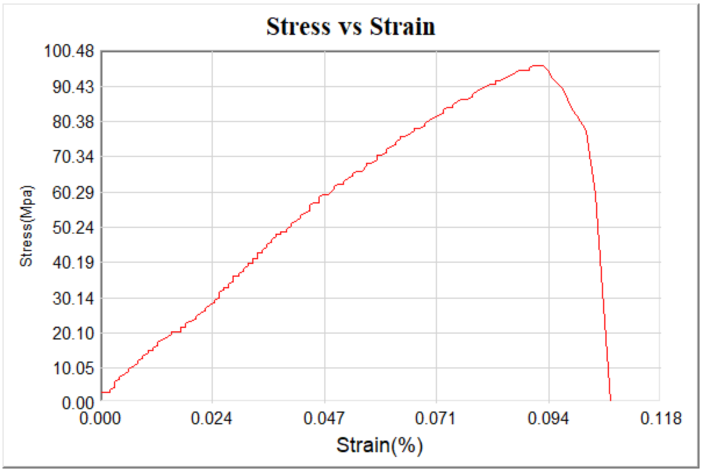


Figure 9. Stress Vs Strain curve for sample 3

The stress vs. strain curve for sample 1 may be seen in the graph up top. Up till 96.44Mpa of force is applied, strain is progressively growing as stress does. Before breaking at 96.44 Mpa, the sample experiences elastic deformation up to that point.

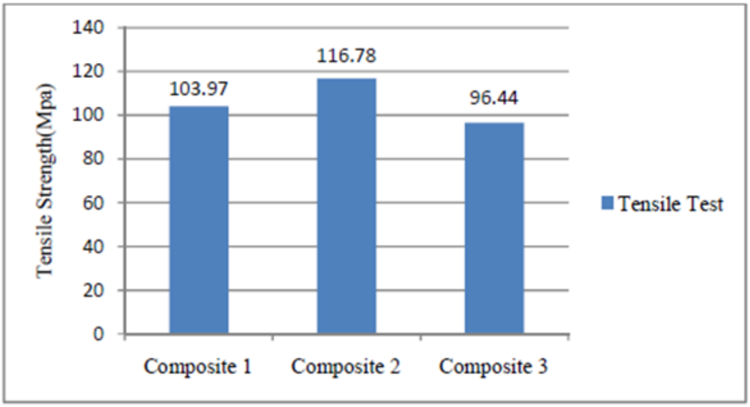


Figure 10. Comparison of three tensile test results

The aforementioned graphic demonstrates that Composite 2 has greater ultimate tensile strength than Composites 1 and 3. The composite 2 has a better tensile strength than composites 1 and 3 because it contains 8% zirconia.

3.3. Hardness Test

The Vickers hardness test can be conducted on samples 1, 2, and 3 Al8011-zirconia composite materials to determine their surface hardness. The test involves the following steps:

3.3.1. Sample preparation

The samples should be prepared by cutting, grinding or polishing a flat surface for the test. The sample should be cleaned free of any debris, burrs or cracks and marked for easy identification.

3.2.2. Test rig setup

A Vickers hardness testing machine is used along with a pyramidal diamond tip. The testing machine is set up to apply a controlled force to the surface of the sample. The magnification and duration of the load should be set.

3.2.3. Test conditions

The surface hardness of each sample is measured by setting the Vickers hardness testing machine to the appropriate load and holding it for the desired time. The test conditions should be consistent for all samples.

3.2.4. Vickers hardness measurement

A diamond pyramid is pressed into the surface of the sample for a set time using a controlled load. The load is removed, and the indent left on the surface of the sample is measured. The indent should be measured using a microscope and the diagonal lengths of the four edges of the indent are taken.

3.2.5. Analysis

The surface hardness of each sample is calculated from the measurement of the diagonals using the Vickers hardness formula. The hardness number is expressed in units of Vickers.

3.2.6. Results

The results of the Vickers hardness test are analyzed, and the surface hardness of each sample is compared. The results can be considered from the perspective of the percentage of zirconia added and can be used to evaluate the surface hardness of the composite materials relative to other materials or applications.

In conclusion, the Vickers hardness test can be used to evaluate the surface hardness of samples 1, 2, and 3 Al8011-zirconia composite materials. The results can help guide further research and development to optimize the surface hardness of the composite materials for specific applications requiring high resistance to wear and tear or scratching.

Figure 11. Hardness Test specimens

Table 4.Hardness Test Results

Parameters	Sample ID	Observed values (Hv)	Average values(Hv)
Vickers Hardness, Hv	Al-96% + ZrO_2-4%	46.3, 49, 52.1	49.13
Vickers Hardness, Hv	Al-92% + ZrO_2-8%	42.1, 45.6, 41.4	43.03
Vickers Hardness, Hv	Al-88% + ZrO_2-12%	51.2, 44.3, 49.3	48.26

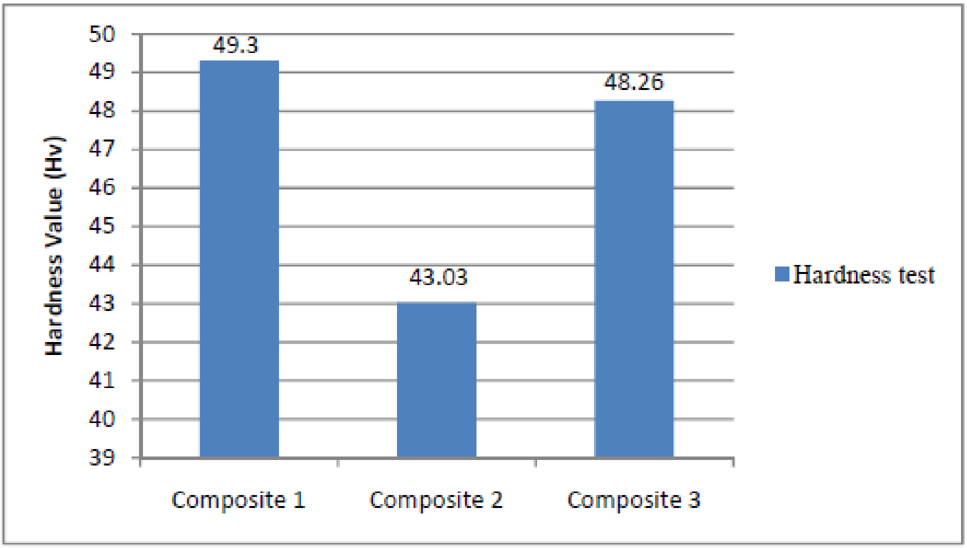


Figure 12. Comparison of three hardness test results

By looking at the above data, it is clear that sample 1 (Al-96% + ZrO_2-4%) is harder than samples 2 (Al-92% + ZrO_2-8%) and 3 (Al-88% + ZrO_2-12%). Zirconia's growth has caused a difference in hardness. As compared to samples 1 and 2, sample 1 is harder.

3.4. SEM Test

Scanning electron microscopy (SEM) can be used to analyze the microstructure of samples 1, 2, and 3 Al8011-zirconia composite materials. The test involves the following steps:

3.4.1. Sample preparation

The samples should be prepared by cutting, grinding or polishing a flat surface for the test. The sample should be cleaned free of any debris, burrs or cracks and mounted on a SEM sample holder.

3.4.2. Coating

Prior to imaging, the sample surface needs to be coated with a conducting material to prevent charge build-up on the surface of the sample during microscopy imaging. The conducting material must be applied evenly across the entire surface of the sample. Examples of materials that could be used include sputtered gold, platinum or carbon.

3.4.3. SEM imaging

The sample is then imaged under high magnification using a scanning electron microscope. Electrons are directed onto the sample surface, causing them to interact with the material, and produce an image.

3.4.4. Analysis

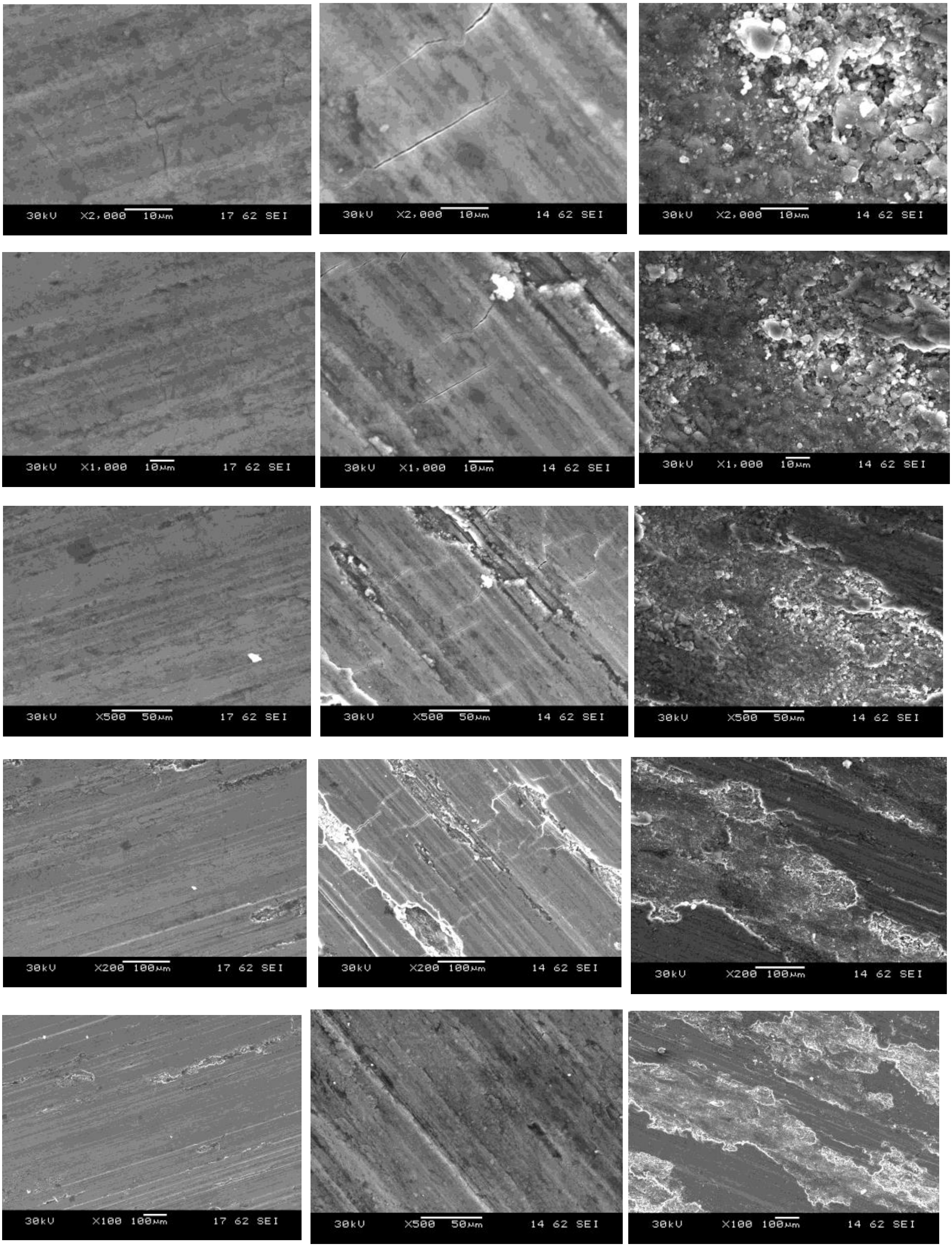
After imaging, the SEM images of the samples can be analyzed. The microstructure of the composite materials, as well as the distribution of the zirconia particles, can be observed and analyzed.

3.4.5. Results

The results of the SEM analysis can help to determine how the zirconia particles are distributed in the aluminum matrix and the overall microstructure of the material. This information can be used to optimize the composition and processing of the composite material for specific applications.

In conclusion, SEM can be used to analyze the microstructure for samples 1, 2, and 3 Al8011-zirconia composite materials. The results of the SEM analysis can be used to guide further research and development to optimize the microstructure of the composite materials for specific applications.

Figure 10. Samples for after wear test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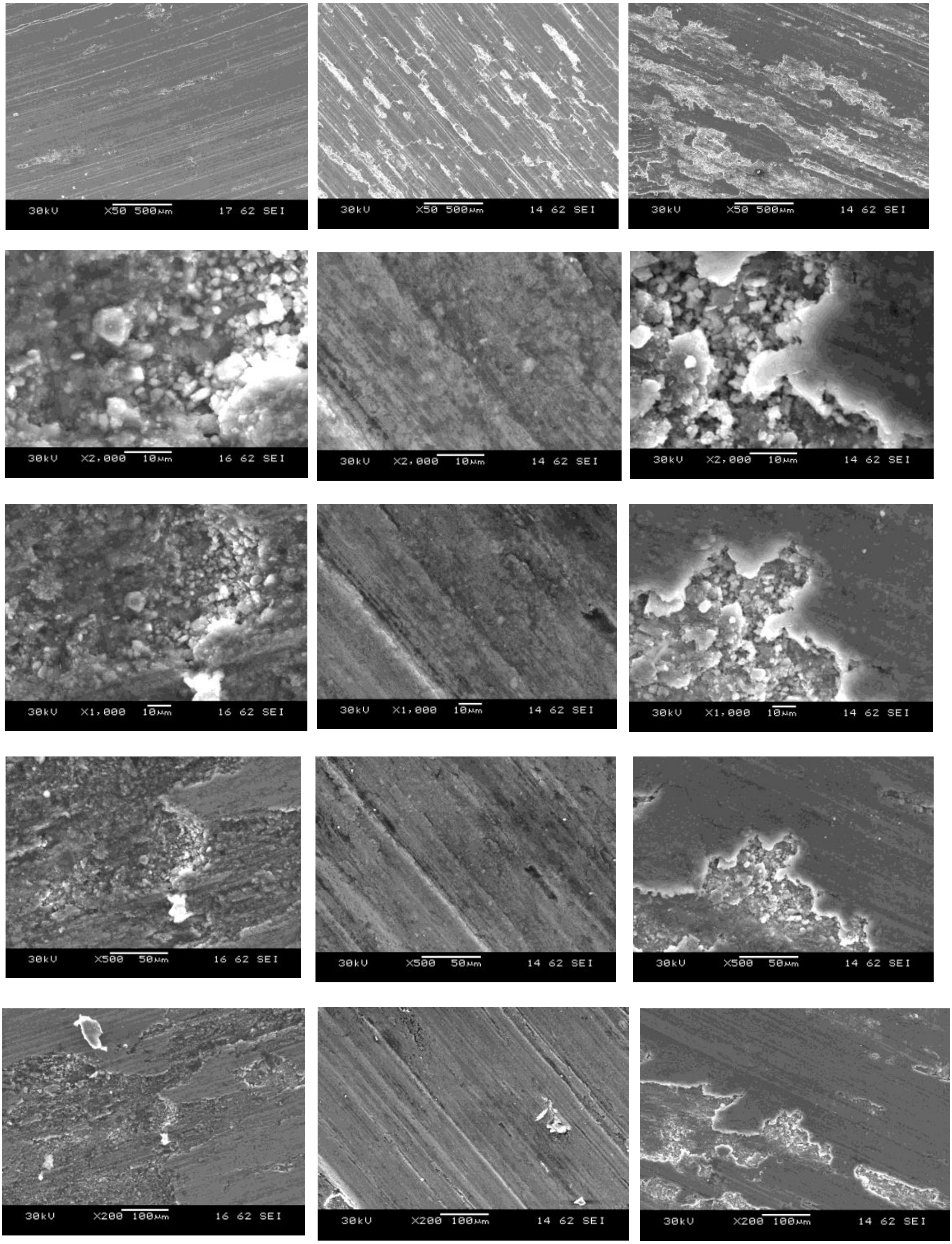
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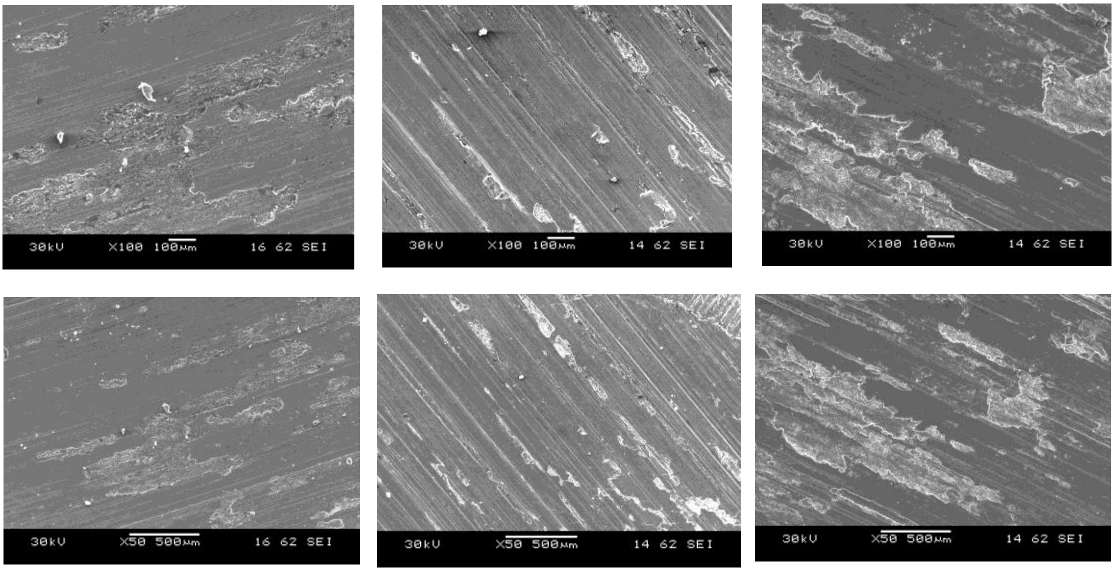

Figure 11. Al 8011- ZrO_2 composites' worn surfaces were captured by SEM in samples 1, 2, and 3

4. Conclusion

The research work is about the investigation of aluminium-8011 metal matrix composite reinforced with Zirconium di oxide [Zro_2] through stir casting method and analysis of mechanical properties of all sample done through mechanical testing methods like wear test, Tensile test, hardness, SEM analysis, By testing all 3 samples, it is possible to finalize the best Sample among all samples. Mechanical properties of composite samples like wear, hardness, tensile and microstructure image are evaluated by using respective test machines. The sample 1 with 4% of Zirconium –di-Oxide reinforced with Aluminum-8011 is showing the highest hardness value than sample 2 and sample 3, By conducting Tensile test through Universal Tensile Machine, This indicates the sample 2 with 8% of Zro_2 show highest tensile strength among other samples. The sample 1 with 4% of Zro_2 is shows lowest Wear rate. The SEM analysis test is also done for the study of micro structural behavior of all samples, how the Zirconoium-Di-Oxide reinforcements distributed in composite materials. The detailed study of Aluminum-Zirconia metal matrix composites shows that sample 1 is the best among all samples.

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Conflict of interest: The Authors have no conflicts of interest to declare that they are relevant to the content of this article.

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