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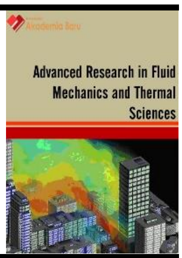

Effect of Yttrium on the Microstructure and Mechanical Properties of A5083 Secondary Aluminum Alloy

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ABSTRACT

The significant economic and environmental benefits of using secondary aluminum alloys are being challenged with the need for selection of alloying elements that is capable of producing secondary castable Al alloys that can be used on the same quality as before, to provide better strength, withstand high-temperature and good corrosion resistance. The interactive effects of Yttrium (Y) additive on the microstructure of A5083 secondary aluminum alloy and how 0.5%, 1.0%, and 1.5% of this addictive affects the mechanical properties of the secondary alloy was investigated. X-ray diffractometer and FESEM spectroscopy, coupled with an optical microscopic test were used for characterization, while the mechanical properties testing involves tensile and impact strength test. The modifications formed an intermetallic compound which causes the size of the dendritic phase to decrease along with increasing the grain size to 40 µm. The Al-Mg-1% Y alloys display greater tensile strength, Young modulus, and elongation, these enhancements were expected to improve the service integrity of the secondary A5083 aluminum, especially for structural, marine, and building construction. The impact shock absorbed by the modified alloy and the micro hardness test result also indicated that the addition of Y up to 1 wt.% gives the best modification to the A5083 secondary aluminum alloy.

1. Introduction

The increasing application of aluminum in packaging industries, transportation, construction and electrical engineering has significantly lead to a dramatic increase in aluminum production. For example, the production of primary aluminum increased from approximately 38, 938 metric tons in 2006 to 58, 890 metric tons in 2016 [1]. Thu, showing an average of 15.7 % annual increase

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throughout a period of 10 years, with a demand increase projected to around 97 million tons by the year 2020.

Aluminum production is an energy-intensive industry reported to have been responsible for about 1 % total man-made greenhouse gas emission [2-3], with about 40 % direct emission from production and 60 % indirect emission from electric energy use. A comparative analysis of primary aluminum production and recycling of aluminum has positioned the secondary aluminum production as a basis for aluminum sustainability. Furthermore, recycling of aluminum products has been estimated to have utilized about 5 % of the energy and also responsible for emitting nearly 5 % of the greenhouse gas as against that of the primary production [2, 4-5].

Secondary aluminum production has been considered as a major driver towards sustainable aluminum use as it accounted for above third the total aluminum used in the world today. In 2007, secondary aluminum production was close to 18 million tons and a global recycling target for used aluminum beverage cans was pegged to about 75 % by 2015 [3]. Presently, large amount of recycled aluminum was generated from old aluminum scraps or byproducts and excesses or waste from rolling and extrusion. Because of the large volume of these aluminum byproducts and/or scraps, coupled with the excellent recyclability, aluminum have the highest possibility of regular recycling without altering its atomic structure. Hence, the declaration that the life cycle of an aluminum product is actually a renewable “cradle-to-cradle”.

Yellishetty *et al.,* [5] reviewed the earlier work of Reuter *et al.,* [6], Ayres *et al.,* [7] on improving sustainable material use through innovative recycling strategies. Their comment identified that the logistics of material grouping based on the residual concentration is the most serious and daring phases in metal recycling processes because mingling of metallic products and other alloying elements through changing life cycle stages leads to buildup of contaminants, causing lots of constraints during re-melting and a great challenge to the intention of producing quality materials. More so, Nakajima *et al.,* [8] and Das *et al.,* [9] are of the view that if scrap is pre-treated and/or sorted appropriately, the recycled aluminum can be utilized for almost all aluminum applications.

However, since majority of the aluminum recycling is done in open loop cycles where there is a high degree of uncertainty in validating the complete transformation of primary aluminum and alloying elements, the quality of secondary aluminum from such a recycling route was and will continue to be a major challenge in metal recycling processes [10-11]. Often, melt treatment modification is applied to these secondary alloys to maintain and improve the working properties by adding other alloying elements in to the alloy system as modifiers [12-14].

Rare-earth metals and other elements found in group five of the periodic table such as lanthanum (La) and cesium (Ce), antimony (Sb) and arsenic (As) were reported to have influences the morphology of a silicon structure Al-Si-Cu-Mg alloy system [15]. For example, Yile [16] found that Lanthanum was responsible for speeding up the age-hardening growth of 6061 alloys. While other rare earth elements such as Yttrium was reported to have increased the strength of Al-Zn-Mg-Cu alloy at a high temperature by reducing the grain size of the as-cast alloy, which results to improvement in the nucleation ratio, during artificial aging [17-19]. Bethencourt *et al.,* [20] examine the influence of lanthanide towards the pitting corrosion of AA5083 alloy, their findings revealed the effectiveness and ecological advantage of lanthanide salts for impeding the corrosion of Al-Mg AA5083 alloy when compared to the popular chromate inhibitors.

From the review of work done so far, some useful studies that deals with the microstructural modification and enhancement of the mechanical properties of primary Al-Mg and Al-Si-Cu-Mg alloy system have been undertaken. However, there is a shortage of information on the secondary Al-Mg alloys system. Therefore, this research studies the interactive effect of Y on the microstructure and mechanical properties of A5083 secondary aluminum alloy.

2. Methodology
2.1 Sample Preparation

The elemental composition of the secondary A5083 aluminum used in this study is presented in Table 1, this aluminum alloy was supplied under license of MAA SDN BHD Malaysia. The supplied ingot was cleaned, dried and cut into smaller pieces, and then placed in a silicon carbide crucible shown in Figure 1(a), the melting was carried out under a temperature range 880 °C – 900 °C in an induction furnace. Yttrium (Y) in varying concentration of 0.5 %, 1.0 % and 1.5 wt.% was introduced to the molten. A duration of 10 min interval was observed between each material addition stage to achieve better homogenization and dissolution, Zirconia coated steel rod was used to stir the melt for about 40 s to ensure that dross and other impurities were removed before pouring at 900 °C. The molds as presented in Figure 1(b) are pre-heated to 600 °C in a firing furnace for 30 minutes before the casting operation.

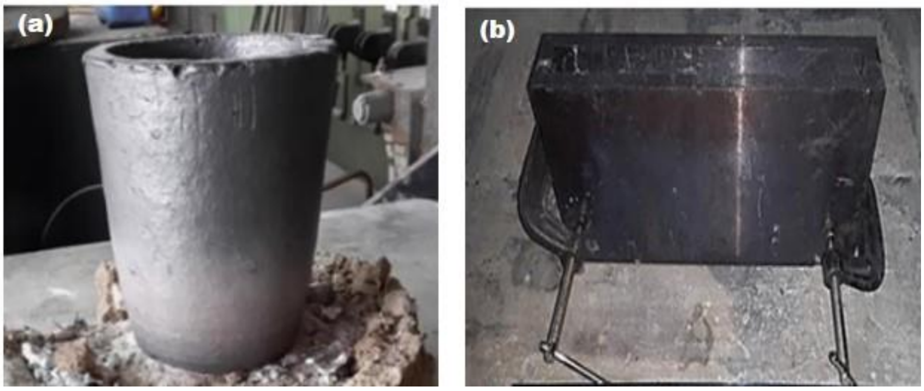


Fig. 1. (a) Silicon carbide crucible (b) Mold used

Table 1
Chemical composition of the A5083 secondary aluminum alloy

Elements	Al	Si	Cu	Fe	Mn	Mg	Zn	Balance
Weight (%)	Bal	0.4	0.1	0.4	1	4.9	0.25	Al

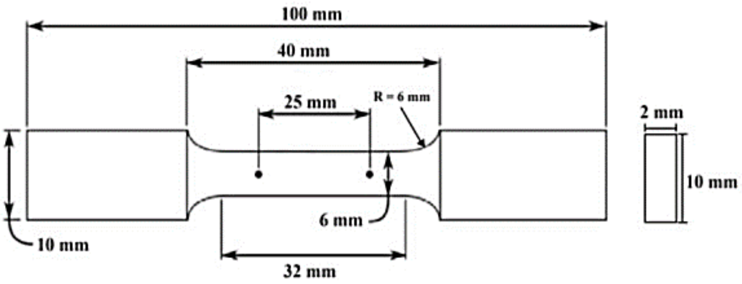
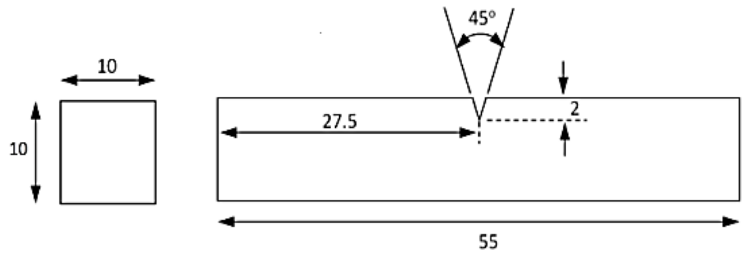
2.2 Materials Characterization

The as cast alloy is cut to a suitable size, cold mounted in a resin and grind with a finer Sic paper. A mirror smooth surface was achieved by polishing with a 0.5μm silica suspension, a mixture of 90 % H_2O and 10% HF was used for etching of the polished samples. X-ray diffractometer (XRD), Siemens–D500 was used for the phase identification on the samples using Cu Kα line generated at 40 kV and 35 mA at a scan rate of 0.05°/sec for 2θ of 20–80 degrees. The chemical microanalysis of the secondary alloys was carried out using energy dispersive spectroscopy (EDS) while, the metallographic analysis was carried out using optical microscope and (FESEM), Carl Zeiss, Germany.

2.3 Mechanical Testing

Specimens for the tensile strength and impact energy testing were prepared according to ASTM E-08, and the cutting to shape was done with the EDM wire cut. The tensile test was conducted using a Universal testing machine (model 5982) set to a crosshead speed of 1mm/min. while the impact test was carried out with Zwick pendulum impact tester. A Vicker's hardness value obtained from three different points on each sample using a load of 5 Newton was computed to represent the hardness of the modified A5083 secondary alloy. All these testing were carried out at ambient temperature. Table 2, contains the detail illustrations of the samples prepared.

Table 2
Samples for mechanical testing

Test	Referenced standard	Diagrams
Tensile strength	ASTM E-08	
Impact test	ASTM E-08	

3. Results
3.1 Microstructural Analysis

The structure of the A5083 secondary alloy was overwhelmed by wide equiaxed grains with coarsening dendritic arrangement which spread continuously along the grain boundaries, showing a severe dendritic structure of the Al-Mg-Si-Zn alloy, with a greater branch distance between the dendrites and the grain size of about 60~80 µm.

In all likelihood, the addition of Y has affected the structure of the treated A5083 secondary alloy. It is clear that greater branch distance between the dendritic arrangements has reduced, and the dendritic structure of the Al-Mg-Mn-0.5 % Y alloy became much pronounced with a uniform average grain size of about < 30 µm as illustrated in Figure 2 (a) and (b). More so, as the percentage of Y increased to 1.0 %, a slight changed in terms of the volume fraction of the dendritic phase along with an increase in the grain size to 40 µm was observed in the microstructure Figure 2 (c) and (d).

However, a decrease in grain size and reduction in volume fraction of the dendritic phase was revealed as percentage of Y increases to 1.5 % Figure 2(e) and (f). Thus, confirming the speculations by Yile and Zhang *et al.,* [17-19] that rare earth elements such as Yttrium can be able to improve the strength of Al-Zn-Mg-Cu alloy at a high temperature by decreasing the grain size of the as-cast alloy and increasing the nucleation ratio.

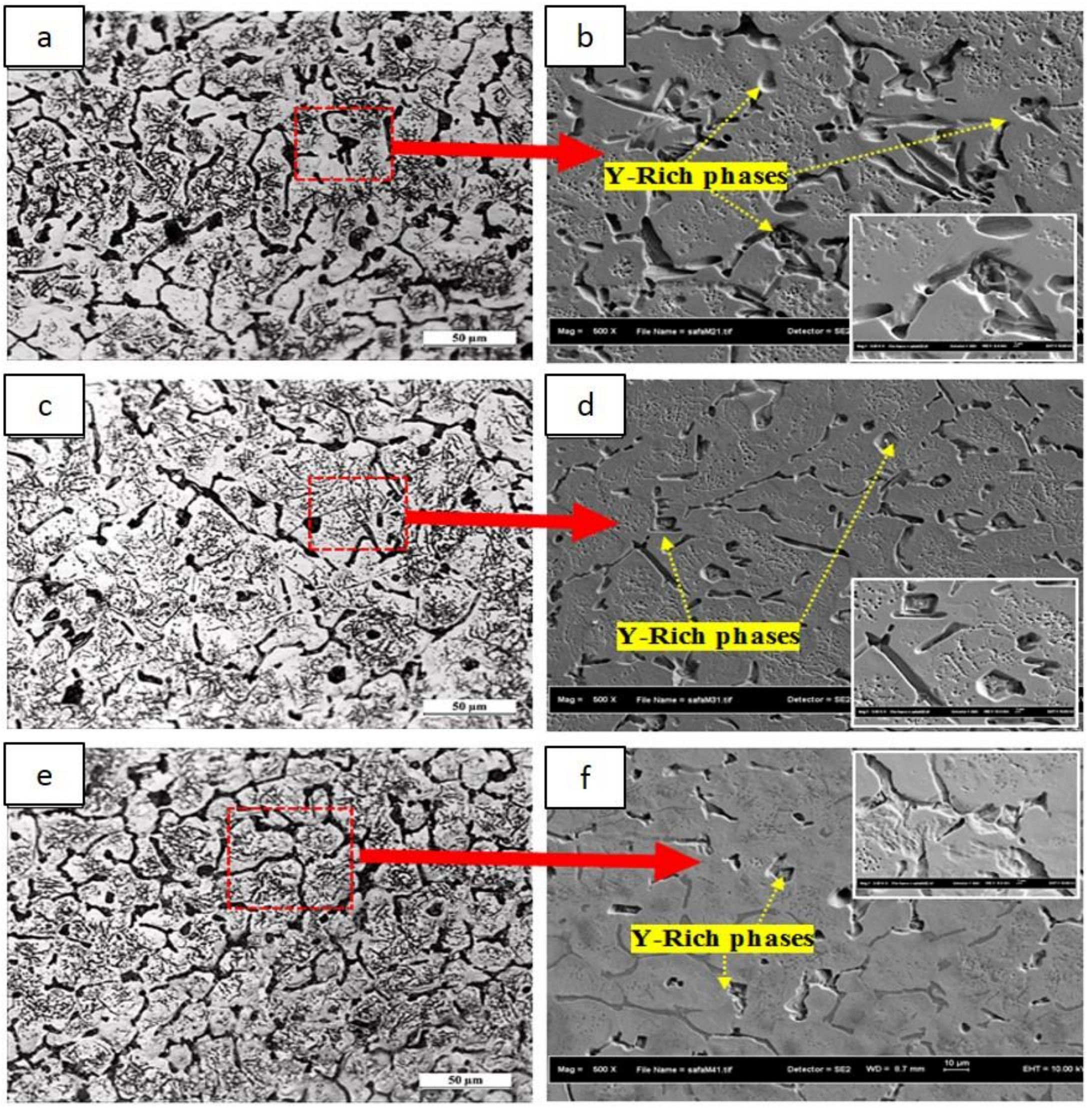


Fig. 2. Optical (left side) and scanning electron micrographs (right side) of the secondary A5083 alloy with and without the addition of Y; (a, b) 0.5 wt.% Y, (c, d) 1.0 wt.% Y, and (e, f) 1.5 wt.% Y

Results obtained from chemical microanalysis using EDX Figure 3(a), confirmed the matrix phase of the base alloys as Al rich and the dendritic structure is a compound of the Al, Si and Mg rich phases. A large number of residual phases exist at grain boundaries, and the white secondary phase shown in spectrum 1 was identified as Al-and Mg-rich, which may be the mixture of supersaturated solid solution α (Al) and Al_3Mg_2.

While, the grey phase in spectrum 2 represents the impurity phase, which may be the matrix α (Al) with solute of Zn, Mg, Si elements. Figure 3(b), shows the composition of the obtained phases after the addition of the Y, however, the dendritic structure of the alloy is still Al-and Mg rich, accompanied with precipitates phase, which belongs to the intermetallic compounds of Al, Mg, Si, Cu, Zn, and Y.

To make sure the modification of the rare earth elements such as Y are successfully formed with the elements of the binary or ternary compounds, elemental dot mapping was conducted on the A5083 modified alloy with 1.0 % Y. Careful observation indicates that the entire alloying elements of the modified secondary aluminum alloy have been uniformly formed along with the formation of Y element on the boundaries of dendritic and precipitated inside as well.

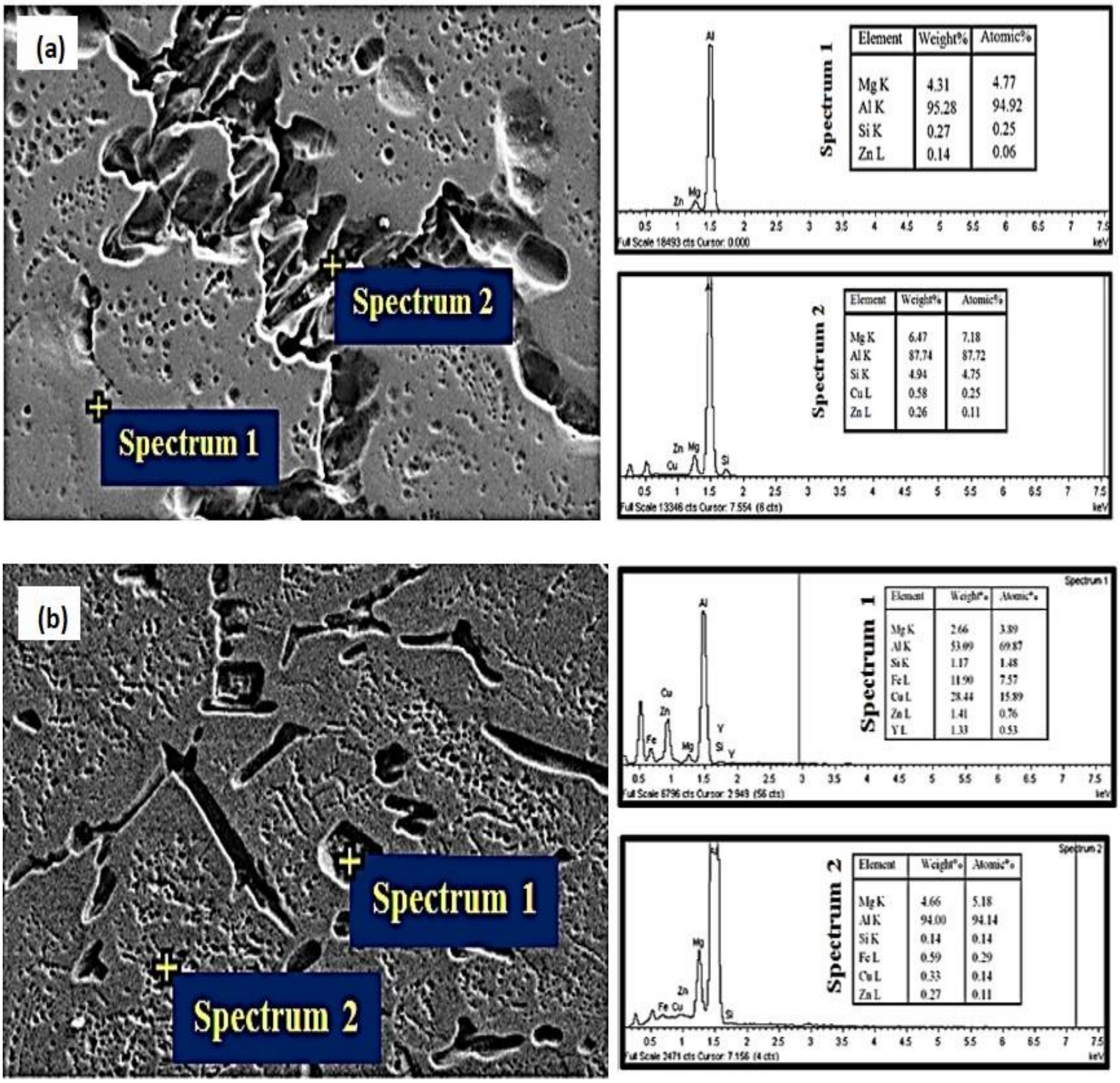


Fig. 3. EDX analysis of spectrum 1 and spectrum 2 of (a) A5083 base alloy (b) 1.0 wt.% Y modified A5083 alloy

Supporting the discussion on the modifying effect of Y, the formation of phases due to the modification of Y in secondary A5083 alloy is further studied by analyzing the samples through X-ray diffraction. Figure 4, presents the diffractogram of the treated and untreated A5083 secondary alloy. Careful observation of the detected Al phase of the binary Al_3Mg_2 alloy indicates the formation of Y_5Al_3, YAl, MgYZn, Mg_3YZn_6 and Mn_2YSi_2 compounds in the treated alloys as a direct consequence of Y addition. The peaks intensity of these compounds varied in accordance with the amount of Y added, as earlier observed by [16]. In this study, the sample with 1 wt.% Y addition obtained the highest intensity, and the reason may be associated to the high volume of the detected intermetallic compounds which may possibly translate to effect the dendritic phases and the grain size.

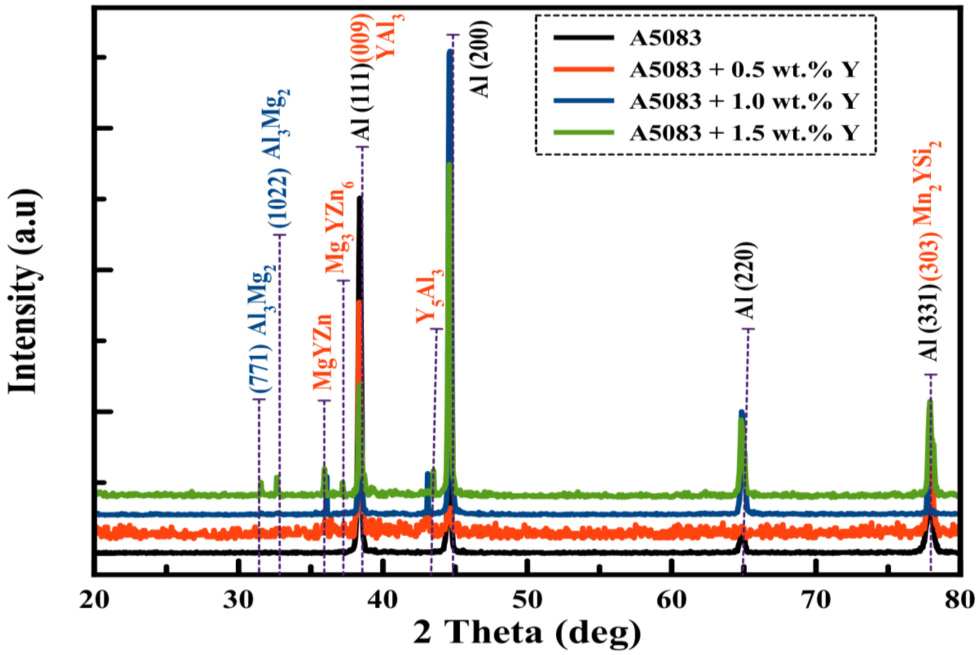


Fig. 4. X-ray diffractogram of unmodified and modified A5083 secondary aluminum alloy with varying concentration of Y

3.2 Mechanical Properties

The tensile properties of A5083 secondary aluminum with different amounts of Y addition are illustrated in Figure 5. There was a significant change in the tensile properties of the secondary alloy, but these changes are mainly attributed to the remarkable variation in the microstructure. Accordingly, the best elongation, UTS, and E of 10.2 %, 192 MPa, and 75 GPa for A5083 alloy was obtained with the addition of 1.0 wt.% of Y, due to a high volume fraction of Y-rich precipitated, such as Y_5Al_3, YAl, MgYZn, Mg_3YZn_6 and Mn_2YSi_2 that are formed accompanying with variation in the grain size.

Increasing the amount of Y also results to a decrease in mechanical properties, suggesting therefore, that the volume of yttrium added in to the recycled Al−Mg-Cu alloys must be restricted within a cogent range. Bethencour *et al.,* [21] proposed that, a homogenous dispersal of RE in Al−Mg-Cu alloys can inhibit dislocation slipping and improve the strength even at an elevated temperature. Looking at the FESEM result in Figure 2, increasing the content of yttrium leads to coarsening and growth in size of the precipitate and thus induce a gradual change in shape from flake to irregular spherical shape. It is right therefore to emphasise that these remarkable changes strengthens the alloy and inhibit dislocation slipping, yielding to an increase of the UTS, which is conforming to the work of Park and Ardell [22]. However, results from this experimental study indicated that, addition of 1.0 % Y appears to provide maximum strength to the modified A5083 secondary aluminum alloy.

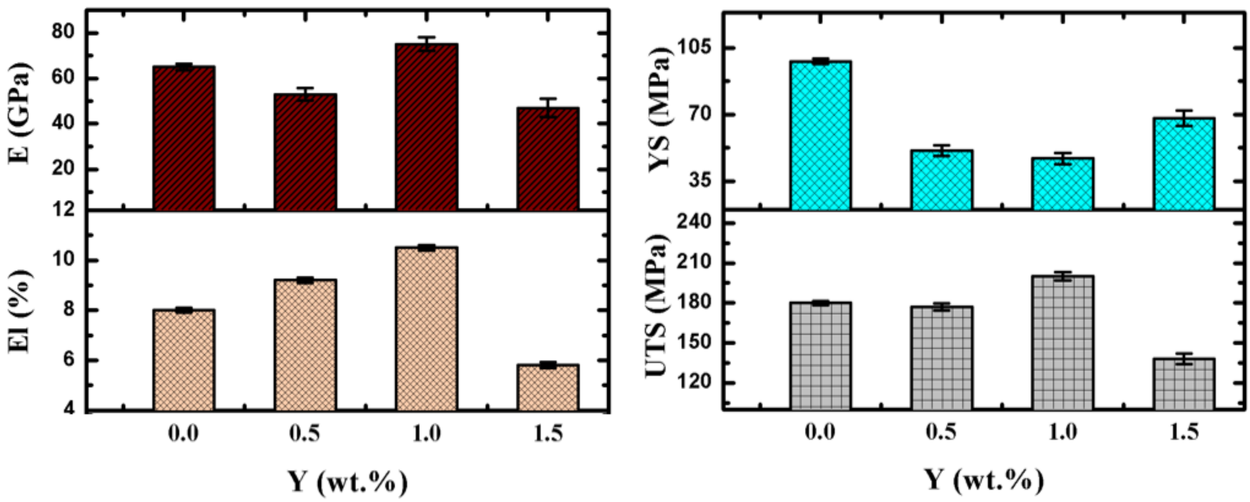


Fig. 5. Result of tensile test showing the YS, UTS, El% and elasticity modulus of the modified A5083 secondary aluminum alloy with varying concentration of Y

The fracture surfaces of the tensile strength tested samples were also investigated to examine the type and mode of failure. Coarse Al planes indicating a mix mode fracture of intergranular and some dimpling areas in between was observed at the fractured surface of the A5083 base alloy without any addition Figure 6(a). The fracture surface of samples with 0.5% Y addition Figure 6(b), exhibits fine Al planes associated with mixed mode fracture of intergranular and transgranular. While samples with 1.0 and 1.5 % Y showed a mixed mode of ductile with a high percentage of dimples as shown in figure 6(c) and d respectively. Indicating that the plastic strength of the material has been of poorer quality at this time; as earlier reported by Shen *et al.,* [23] that as-cast aluminum alloys fails as transdendritic mode.

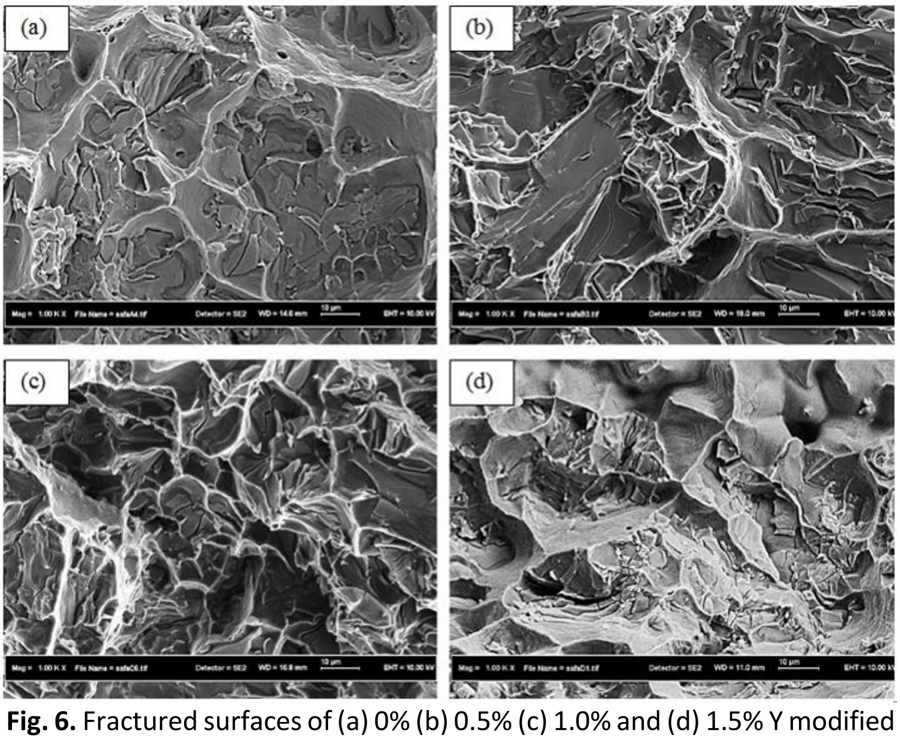


Fig. 6. Fractured surfaces of (a) 0% (b) 0.5% (c) 1.0% and (d) 1.5% Y modified secondary alloys after tensile testing

Figure 7 describes the correlation between the energy absorbed by the modified secondary alloys with optimal concentration of Y addition. The absorbed energy value for the base alloy is 6.0 J, whereas it increased to 9.5 J after 1.0% Y addition. The measured impact values for 0.5% and 1.5 % alloys were 6.7 and 5.7 J, respectively. This unprecedented result suggest that the impact toughness of the modified secondary alloys depends mainly on the morphology [23], Al dendrite size and intermetallic Y- rich phases [17]. Hence the reason for a better impact strength of 1.0% Y modified secondary alloy. Different behavior was observed in the effect of Y additions on the modified and un-modified A5083 secondary aluminum alloys. Such as, a general enhancement to the hardening response of the modified alloy as shown in Figure 7.

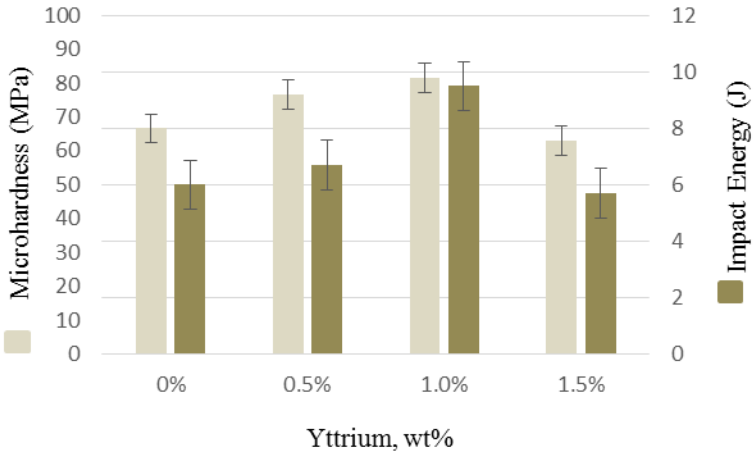


Fig. 7. Absorbed impact energy and hardness values for modified and unmodified A5083 secondary aluminum alloy

In particular, the maximum hardness increased from 66.6 MPa for the base A5083 secondary aluminum alloy to 81.55 MPa for samples containing 1.0 wt.% Y, which happen to be the maximum recorded. However, the maximum hardness was decreased to 63 MPa when the Y content was further increased to 1.5%, which might be as a result of the high percentage of porosity, as narrated by [14, 23] that micro-cracks and pores at the matrix–intermetallics interfaces may likely results in brittleness of the material. The increase in hardening response at 1.0% Y may be a result of the Y solid solution strengthening and grain refinement.

4. Conclusions

This study strongly support the assertion that rare earth metals, especial Yttrium contributes to refinements in most aluminum alloys. It is also found to be responsible for the existence of heterogenic crystallization nuclei in A5083 secondary aluminum alloys. Hence, recommended for use in melt refinement/treatment of secondary aluminum alloys. The refining effect of Yttrium in A5083 alloys is mainly on the microstructure in terms of volume fraction of the dendritic phase and the grain size. However, the addition of Y up to 1.5% into secondary Al–Mg alloy can induce finer and denser precipitate when compared to the unmodified alloy. The Al-Mg-1% Y alloy demonstrate a higher value of Young modulus and elongation, which positively improve the UTS of the treated A5083 secondary aluminum compared to base secondary aluminum. The results of the impact and micro hardness test in this study also indicated that 1 wt.% Y addition offers the optimum modification to the A5083 secondary aluminum alloy.

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