Effect of Cerium and Praseodymium additions on impact toughness of AA5083 alloy at room temperature and sub-zero-temperature

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Abstract: The structural components made of AA5083 alloy are sometimes subjected to shock loadings during their usage. Thus, high impact toughness is a desirable property in this state for proper application. Therefore, modified AA5083 alloys with rare earth elements REEs (REEs = Ce and Pr) additions, that have been produced by in situ casting technique under inert gas (Argon) condition has strong tendency to improve the impact toughness of AA5083 alloy. The amount of REEs (REEs = Ce, and Pr) additions was in the range of (0 ≤ wt. % Of REEs ≤ 1).The tested standard specimens were subjected to Charpy impact testing at room temperature and sub-zero temperature. The obtained results were qualitatively and quantitatively interpreted Quantitatively, it was found that the inclusion of Ce and Pr additions improved the impact toughness of the AA5083 alloy. More so, it was observed the impact toughness increased with increasing percentage of Ce or Pr. It was noticed that the performance effectiveness improvement of Ce addition was more than Pr addition. Regarding the influence of temperature on impact energy, it was observed that the impact energy values for the modified AA5083 alloys were slightly higher in the case of sub-zero temperature than in the room temperature. Qualitatively and based on the SEM images of fracture surfaces, it was found that the nature of the fracture was ductile fracture for all the tested samples.
Key - words: AA5083 alloy, impact, toughness, Cerium, Praseodymium, Charpy.

1 Introduction

The toughness of a material can be defined as the ability of a material to absorb sudden shock and deform plastically before breaking or shattering. [1]. It is usually closely related to material plasticity (it means a higher plasticity leads to higher toughness). [2, 3]
The toughness is one of the major mechanical properties of structural materials which can be estimated from the stress-strain curve through the area under the curve or via the Charpy and IZOD impact tests which are often used. [1]
Charpy impact testing is a well-known method to estimate the impact toughness of the materials [2], it is widely applied in the industries due to its affordability, ease of performance at wide range of temperature and results can be obtained quickly [4]
The Charpy impact test can be performed out according to one of the following standards, ASTM E23, ISO 148, BS 131-4, DIN 51 306, and EN 10045-1.
Charpy tests are very good indicators for comparing the toughness of the materials. Where a brittle material will absorb a little amount of energy (i.e. Need a little impact energy for fracture) while the ductile material absorbs more amount of energy. (I.e. need huge impact energy for fracture)[5, 6]
The results of impact tests can be assessed quantitatively and qualitatively. The quantitative results are the amount of energy required for material fracture, while the qualitative results are obtained via fracture morphology of the fracture surface. Where the brittle fracture encompasses both intergranular and cleavage fracture, while the ductile fracture includes failure by plastic instability or cavitation [7].
It has been reported that the impact toughness of the materials is affected by many variables such as the sample size, notch size, microstructure, and temperature [2, 3, 8, 9].
With respect to the influence of temperature on fracture toughness, Al- alloys like other FCC structure materials do not show any sudden changes in fracture behaviour with a temperature change. Where the materials with BCC structure exhibit a ductile to brittle transition with decreasing temperature under impact load [9]

In general, the impact toughness of coarse-grained material decreases with decreasing testing temperature [9]. But in some nanostructured materials, the impact toughness increases with decreasing temperature as a result of increasing both the strength and the ductility of the nanostructured materials [9-11].
The effect of temperature change on the impact energy of AA5083 alloy and Sic/AA5083 alloy was studied. A slight deviation in impact energy with temperature change was observed [9, 12]
Regarding the effect of rare earth elements REEs additions, many studies have been carried out on the Al-alloys. Meanwhile, the ability of the REEs to improve the Impact toughness of Al-alloys directly or indirectly via improving its ductility was confirmed.
The effect of the rare earth elements REEs (La and Ce and Sr) additions on the mechanical properties of A356 alloy have been studied. It was found that REEs additions enhanced the ductility (i.e. improved impact toughness), where Ce addition had less performance as compared with La and Sr.[13]
Another study showed Adding of REEs (REEs=Ce, and Pr) additions for Al-Fe alloys had an effective influence on the plasticity. Therefore, improvement of its impact toughness is greatly expected. [14]
A study on the 5052 alloy also confirmed that the addition of Er had a positive effect on the tensile elongation which is beneficial to subsequent plastic deformation processing, thus improvement of impact toughness is expected.[15]
Effect of SC additions on elongation of Al-Si-Mg alloy was investigated. It was found that the 0.8wt. % achieved the best result[16]
Regarding, the effect of the crystal lattices (BCC, FCC, and HCP) of material, the FCC and many of HCP structures did not exhibit a ductile-brittle transition DBT and remained ductile at all temperatures, while the BCC and some HCP structures showed the DBT characteristics.[17] This means that the prediction about the fracture modes for BCC and FCC structure is easy (it's brittle and ductile). While for HCP, it's not easy, but it can be concluded that it's often ductile and sometimes brittle.

2 Experimental work

2.1 Material fabrication.

AA5083 alloy and modified AA5083 alloy with REEs (REEs= Ce, Pr) have been fabricated by in-situ casting technique under degaussing condition (Argon gas) by using induction furnace where the amount of each rare earth element REEs (REEs = Ce, and Pr) additions was in the range of $0 \leq$ wt. % Of REEs ≤ 1 with five different amounts (0.1wt.%, 0.3wt.%, 0.5wt.%,0.7wt.%, 1.0wt.%).Then followed by homogenization process at 450 ˚C for 24 hr.

2.2 Charpy V-notch impact testing

The Charpy impact test was conducted on the AA5083 alloy and the modified AA5083 alloys with REEs (REEs = Ce, Pr, and Ce+ Pr) additions by using pendulum impact tester (model: Zwick-5101) with an alternative hammer of 25 J energy, at the materials science engineering laboratory–UTM, according to ASTM E23 standard [18] at two different conditions Room temp. (21 ± 3) °C. and sub-zero temp. (-10 ± 3) °C. Where the setup of Charpy impact test is shown in Fig.1. The explanation of the test with more details is as follow:

2.2.1 Specimen preparation

The geometry of Charpy impact test samples, were according to ASTM E23 standard as shown in fig .1a. Where the specimens were cut by wire cutting machine to get accurate dimensions and it was rectangular in shape (55 mm length and of square section, with 10 mm sides, includes a V-notch in the centre of the length). Where the V-shaped notch was often used in the Charpy impact specimen for the sake of controlling the fracture process via concentrating stress in the minimum cross-section area.
The V-notch was machined by milling cutter machine and it was 2 mm deep, with 45°angle, and with a root radius of 0.25 mm. After that, the surfaces of the samples were polished up to 3µm, cleaned well especially the v-notch by compressor air, then by acetone. The obtained dimensions was checked with a micrometre before each specimen were tested.

2.2.2 Test Procedure

After the sample preparation, it was placed horizontally, where the v-notch facing was on the opposite side of the pendulum contact point, and then the pendulum was raised up to a known height and allowed to fall. The energy absorbed at fracture of the sample was read directly from the instrument gauge.
The average absorbed energy of three Specimens that have been fractured completely (i.e. two separate parts) was recorded as well as the fracture

surface appearance of tested specimens were studied via PV- SEM technique.
To perform the test under sub-zero condition, the test was carried out with the same method for the room temperature condition, the difference was only in using refrigerant gas, where the cooling method was performed in-situ to get accurate test temperature as possible. The gas was sprayed on the sample that has been connected with thermocouple type-K for measuring the sample temperature. When the sample temperature reached the desired temperature, then the sample was struck by the hammer of the pendulum

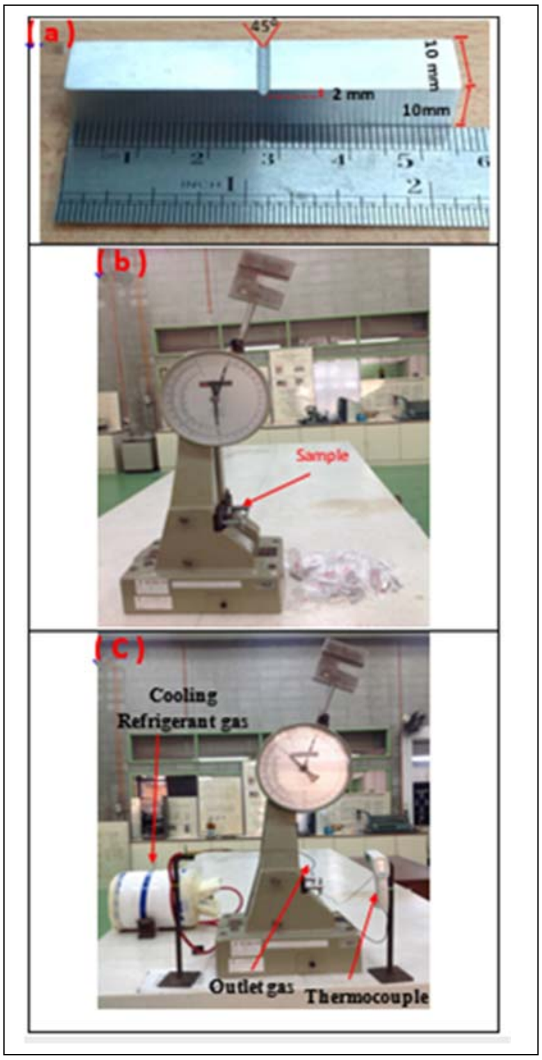

Fig.1 Charpy impact testing machine (a) Standard Charpy V-notch impact test specimen (b) set-up at room temperature (C) Set-up at sub-zero temperature

1.1 Preface

The principle of the Charpy impact test involves breaking the standard sample by a single blow
a hammer of pendulum, under conditions were it defined in standard specifications
The energy (E) absorbed at fracture can be obtained via simple calculations. By the difference in potential energy of the pendulum before and after the test. The energy (E) calculation formula is as follows:[19]
E = m.g. (ho - hf)
Where m is the pendulum mass, ho is pendulum height before Impact, hf is pendulum height after impact, and g is the gravitational acceleration
Where the impact energy (E) consists of two components (Ei+ Ep): Ei is The fracture initiation energy and Ep is the fracture propagation energy.[9]
$E = m.g. (h_o - h_f)$
Where **m** is the pendulum mass, $\mathbf{h_o}$ is pendulum height before Impact, $\mathbf{h_f}$ is pendulum height after impact, and **g** is the gravitational acceleration
Where the impact energy (E) consists of two components (Ei+ Ep): Ei is The fracture initiation energy and Ep is the fracture propagation energy.[9]
Improving the specific absorbed impact energy capability of AA5083 is a key factor in increasing its application in many fields. Therefore, the study highlights the effect of REEs (REEs = Ce, Pr) additions that have been added with various percentages on the fracture and energy absorption characteristics of AA5083 alloy via Charpy impact testing at room temperature and sub-zero temperature.
The study of the shock resistance of modified AA5083 alloys at sub-zero temperature is a worthy subject because the AA5083 alloy has wide applications at sub-zero
The results obtained from the Charpy impact testing have been assessed via both quantitatively and qualitatively.
Where the quantitative results obtained from the tests are the amount of energy required for material fracture. While the qualitatively results obtained from the tests are fracture surface images and that can be used for estimating the fracture type mode (i.e. brittle fracture or ductile fracture) that occurred.

3.2. Quantitative method

The average energies absorbed by the fractured specimens (AA5083 alloy and modified AA5083 alloys with REEs (REEs = Ce, Pr) additions that were obtained from the Charpy impact test are presented in Table 1. An average of three samples was used to obtain the energy absorbed values. Then the data were plotted in form of columns for each rare earth element (Ce, Pr) additions individually, to show clearly its effect on the absorbed impact energy of the AA5083 alloy at room temperature and sub-zero temperature.

3.2.1 Effect of Ce additions on Charpy v-notch impact energy of AA5083 alloy at room temperature and sub-zero temp.

Table.1. Charpy impact test data from AA5083 alloy and modified AA5083 alloys

alloy	Average impact energy (J) ±σ		Increase in energy	
	At room temp.	At sub-zero temp.	Room temp.	Sub-zero temp.
AA5083	19.5±0.043	19.3±0.070	-	-
Modified AA5083 alloy with Ce additions				
0.1wt.%Ce	20.1±0.070	20.3±0.070	3%	5%
0.3wt.%Ce	20.8±0.050	20.9±0.070	7%	8%
0.5wt.%Ce	21.8±0.043	22.0±0.109	11%	14%
0.7wt.%Ce	22.8±0.050	23.0±0.043	17%	19%
1.0wt.%Ce	23.3±0.070	23.5±0.082	19%	22%
Modified AA5083 alloy with Pr additions				
0.1wt.%Pr	19.8±0.109	19.9±0.109	2%	3%
0.3wt.%Pr	20.5±0.141	20.7±0.178	5%	7%
0.5wt.%Pr	21.3±0.070	21.5±0.070	9%	11%
0.7wt.%Pr	22.5±0.070	22.7±0.043	15%	18%
1.0wt.%Pr	23.1±0.109	23.4±0.112	18%	21%

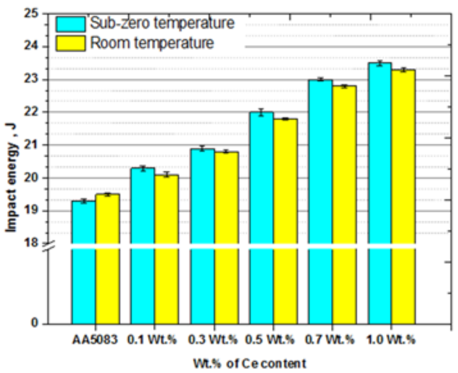

Figure 2: show the average absorbed energy that obtained from Charpy Impact test, vs. Ce element content. The standard deviation was shown on the top of the columns

Fig.2 shows the correlation between the impact energy, j and 0.1wt. % to 1.0wt. % Ce additions content, at room temperature and sub-zero temp.
It was found that the impact toughness was enhanced by the Ce addition in both temperature conditions. It was seen that the toughness gradually increased with increasing addition of Ce additions. It improved by 19% from 19.5 J to 23.3 J. at room temperature and improved by 22% from 19.3 - 23.5 j at sub-zero temperature.

3.2.2 Effect of Pr additions on Charpy v-notch impact energy of AA5083 alloy at room temperature and sub-zero temp.

The influence of 0.1wt. % to 1.0wt. % Pr additions on the impact energy of AA5083 alloy at room temperature and sub-zero temperature was similar to the effect of Ce additions but less effective as shown in Table .1

Fig.3 shows the typical curve of the impact energy with different levels of Pr content (0.1wt. % to 1.0wt. %) Pr, at room temperature and sub-zero temperature. It was observed that the impact energy increased with increasing percentage of the Pr additions which can be improved by 18% from 19.5 J to 23.1 J. at room temperature and improved by 21% from 19.3-23.4 j at sub-zero temperature

Because the REES leads to grain refining and proper phase distribution as well as porosity reduction.[20]. Hence, the improvement of the impact toughness for the modified AA5083 alloys may be attributed to the grain refining and proper phase distribution as a result of REEs additions

In general, the improvement of the impact toughness with increasing percentage of REEs in the limit of wt.% (0.1-1%) additions may be attributed to the presence of a rich second phase with REEs that was formed and played critical role in the improvement of AA5083 matrix ductility.

As a rule, it is hard to acquire combinations of high strength and ductility or high strength and high toughness at the same time. But this can occur in materials that have high tendency for twinning.[21].Thus, the AA5083 alloy and modified AA5083 alloys have combinations of high strength and ductility because they have high tendency for twinning.

The results obtained from the Charpy V-notch pendulum impact test showed higher impact energy absorption at low temperature as compared with room temperature. (i.e. the ductility values of the tested samples increased at low temperature).

This is may be attributed to the deformation twinning that could be responsible for increasing ductility, which is a common phenomenon at low temperature and has been observed frequently in hcp and FCC materials [22-24]

In general and clarifying the aforementioned further at high temperatures, the metals with both BCC and FCC structures had mobile dislocations, therefore they could afford large plastic deformations without being subjected to the fracture. While at low temperatures, the dislocations in BCC structure were no longer mobile because there were no dense-packed atomic planes in the BCC structure, so dislocations in a BCC structure require a certain amount of atomic vibration (thermal energy) to glide. As the temperature drops, that thermal energy diminishes, and the energy needed to move dislocations starts to approach the energy needed to cause brittle fracture. In FCC metals, the dislocations do glide on closest-packed planes, so they are not so dependent on thermal energy to move; thus, lower temperatures don't greatly increase the strength of FCC metals. Their fracture toughness and ductility can actually become slightly higher as the temperature drops

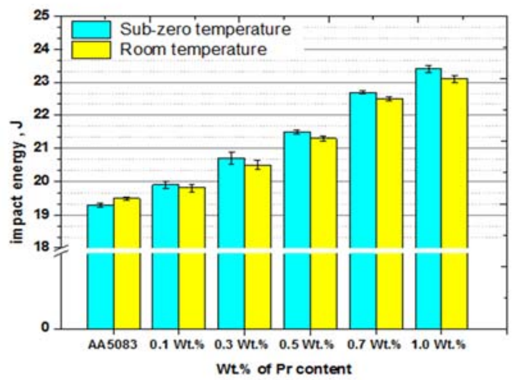

Figure. 3 show the average absorbed energy that obtained from Charpy Impact test, vs. Pr element content. The standard deviation was shown on the top of the columns

3.3 Investigation of Impact Specimens fractography

Qualitatively, results (the PV-SEM images of fracture surfaces) of the Charpy impact tests can be used to estimate the mode of material failure (ductile fracture, brittle fracture or a mix of ductile and brittle fracture).

In general, the qualitatively via the profile of a fracture surface can be obtain information about the nature of fractures that have been occurred. Where a brittle fracture including both cleavage and intergranular fracture appeared relatively bright and crystalline. While a ductile fracture involving failure by cavitation or by plastic instability appeared dull and fibrous [7, 25].

The obtained results via PV- SEM of the fracture surface morphology of the impact specimens of AA5083 alloy, and modified AA5083 alloys with

the highest level of REEs (REEs = Ce, Pr,) additions under two different temperature conditions (at room temperature and sub-zero temperature) was displayed in fig.4.
From Figure 2, it can be estimated that the nature of fracture was ductile fracture with high absorbed energy for all tested samples.
The ductile fracture mode for AA5083 alloy and modified alloys at room temperature and sub-zero temperature has been highly expected because the AA5083 alloy is FCC structure [26], and the FCC structures do not exhibit a ductile-brittle transition DBT and remain ductile at all temperatures[17].
A slight difference in fractographs of the same samples at different temperature conditions (room temp. and sub-zero temp) was observed. This slight difference may be attributed to the difference in ductility, while the observed clear difference in fracto-graphs between the AA5083 alloy and the modified AA5083 alloys as well as among the modified AA5083 alloys themselves may be due to the difference in chemical compositions.
The presence of a harmonic relationship between the values of impact energy and fracture features was an interesting observation. Where a previous study indicated that Charpy impact fractures can be categorized into two general types, brittle and ductile. In the case of brittle fracture (less than 10ft-bl, 13.56 joule) [27]. Since the values of impact energy for all tested samples have been higher than 13.56 j. Thus, the tested samples can be considered as ductile materials that have been confirmed via fracture features observation

4 Concluding remarks

The following conclusions are drawn from the experimental work on the effect of REEs (REEs=Ce, Pr, and Ce+ Pr) additions on the impact energy of AA 5083 alloy.

- The impact toughness of the AA5083 alloy was improved by adding of REEs (REEs = Ce, Pr) additions. Where the performance effectiveness improvement of the AA5083 alloy via Ce additions was greater than Pr additions.

- The modified AA5083 alloy with 0.5wt. % Ce + 0.5wt. %Pr addition showed the highest increase in energy absorption, roughly 21% at room temperature and 23% at sub-zero temperature as compared with AA5083 alloy.

- Regarding the influence of temperature on impact energy, it was found that the impact energy values for modified AA5083 alloys were slightly higher in the case of sub-zero temperature than in the room temperature.

- Provide some information about effect of REEs on the impact energy absorption for AA5083 alloy at room temperature and at sub-zero temperature that may be most useful for applications where toughness property is critical.

- Improvement of impact toughness of AA5083 alloy via REEs addition was a key factor in the development of the alloy and increased its areas of application.

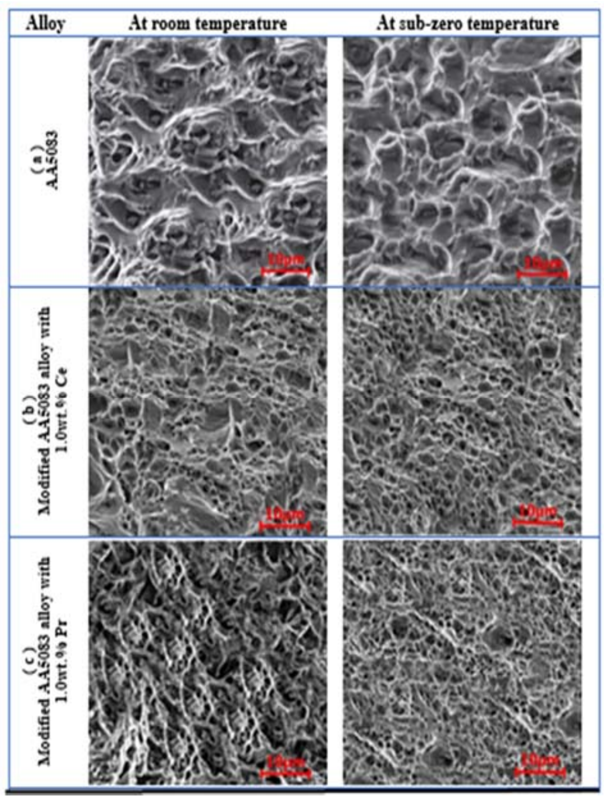

FIG. 4. PV-SEM images fractographs of fracture surfaces of tested samples after impact tests at room temperature and sub-zero temperature (a) AA5083 (b) Modified AA5083 alloys

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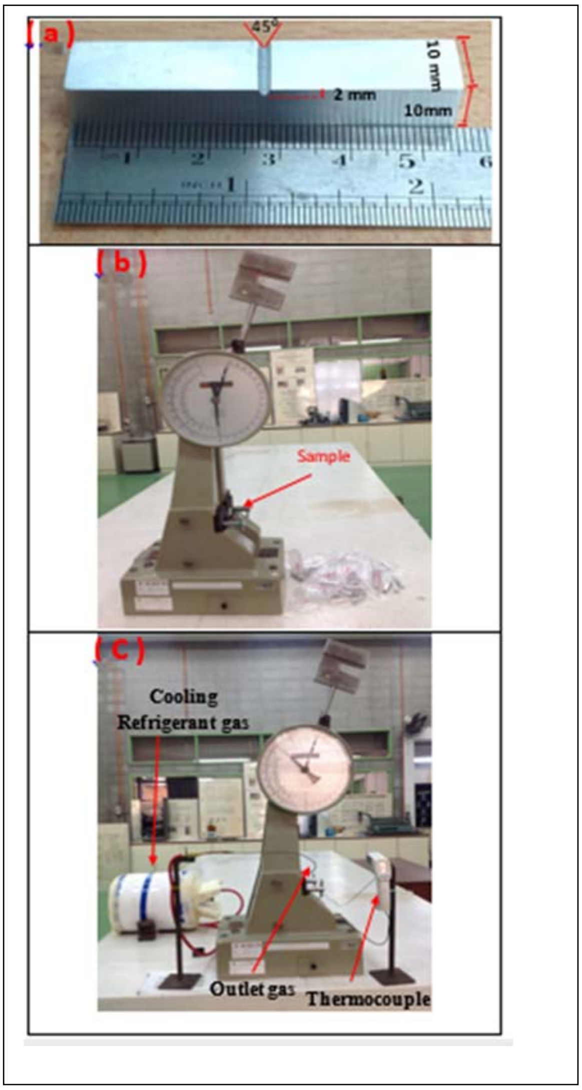

Fig.1 Charpy impact testing machine (a) Standard Charpy V-notch impact test specimen (b) set-up at room temperature (C) Set-up at sub-zero temperature

Table.1. Charpy impact test data from AA5083 alloy and modified AA5083 alloys.

alloy	Average impact energy (J) ±σ		Increase in energy	
	At room temp.	At sub-zero temp.	Room temp.	Sub-zero temp.
AA5083	19.5±0.043	19.3±0.070	-	-
Modified AA5083 alloy with Ce additions				
0.1wt.%Ce	20.1±0.070	20.3±0.070	3%	5%
0.3wt.%Ce	20.8±0.050	20.9±0.070	7%	8%
0.5wt.%Ce	21.8±0.043	22.0±0.109	11%	14%
0.7wt.%Ce	22.8±0.050	23.0±0.043	17%	19%
1.0wt.%Ce	23.3±0.070	23.5±0.082	19%	22%
Modified AA5083 alloy with Pr additions				
0.1wt.%Pr	19.8±0.109	19.9±0.109	2%	3%
0.3wt.%Pr	20.5±0.141	20.7±0.178	5%	7%
0.5wt.%Pr	21.3±0.070	21.5±0.070	9%	11%
0.7wt.%Pr	22.5±0.070	22.7±0.043	15%	18%
1.0wt.%Pr	23.1±0.109	23.4±0.112	18%	21%

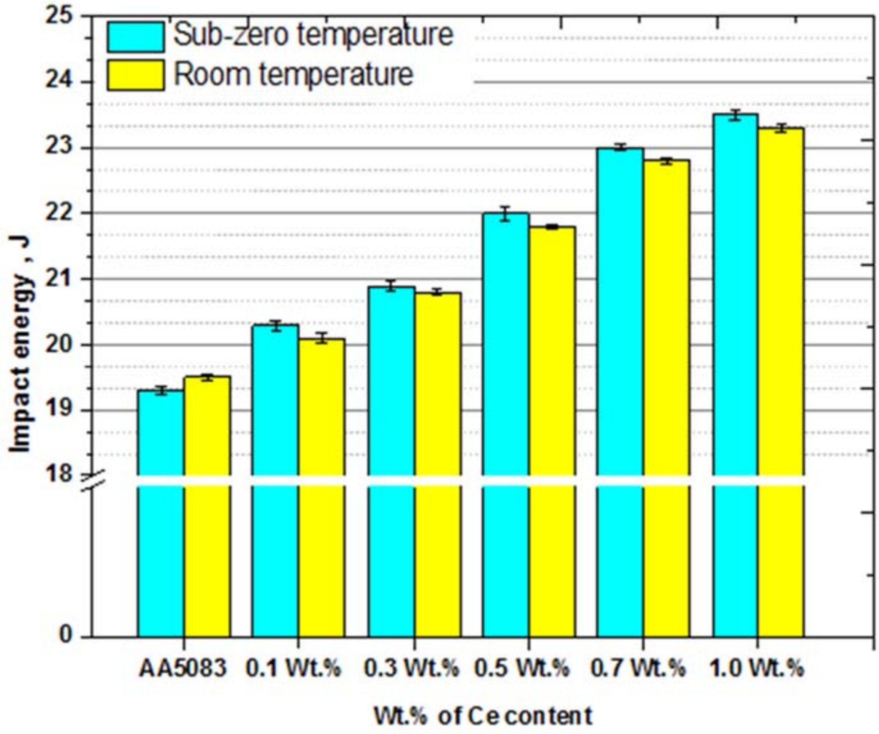

Figure 2: show the average absorbed energy that obtained from Charpy Impact test, vs. Ce element content. The standard deviation was shown on the top of the columns.

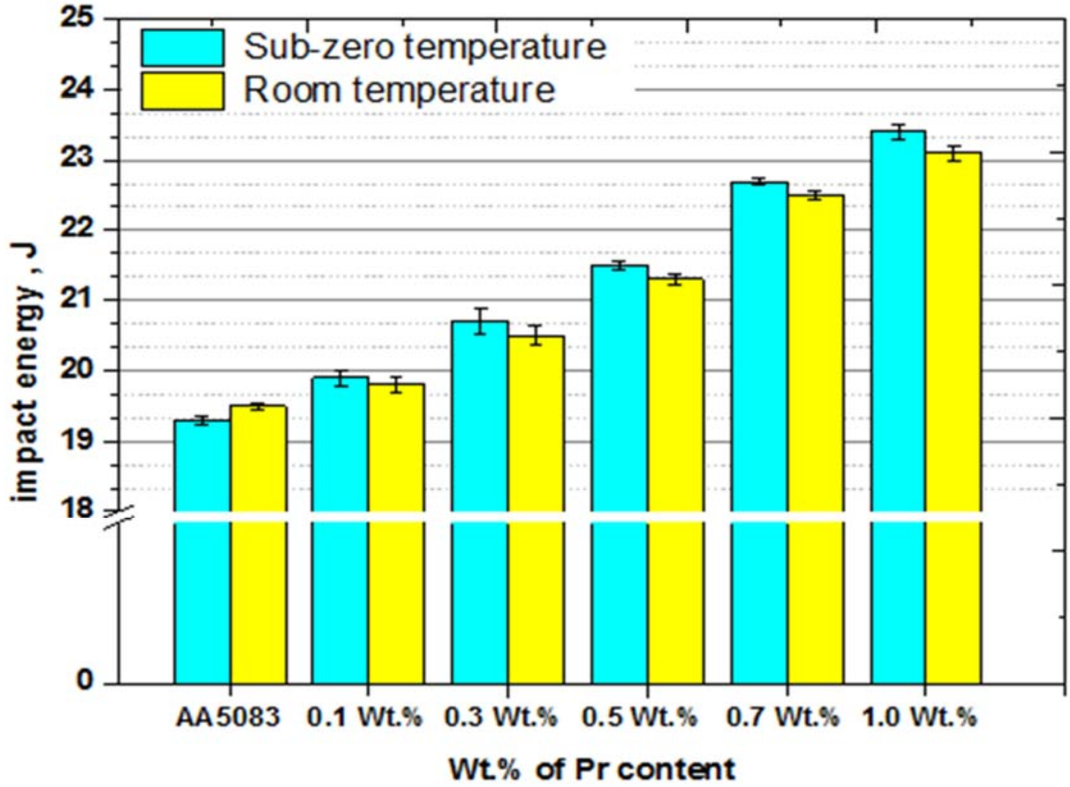

Figure 3: show the average absorbed energy that obtained from Charpy Impact test, vs. Pr element content. The standard deviation was shown on the top of the columns

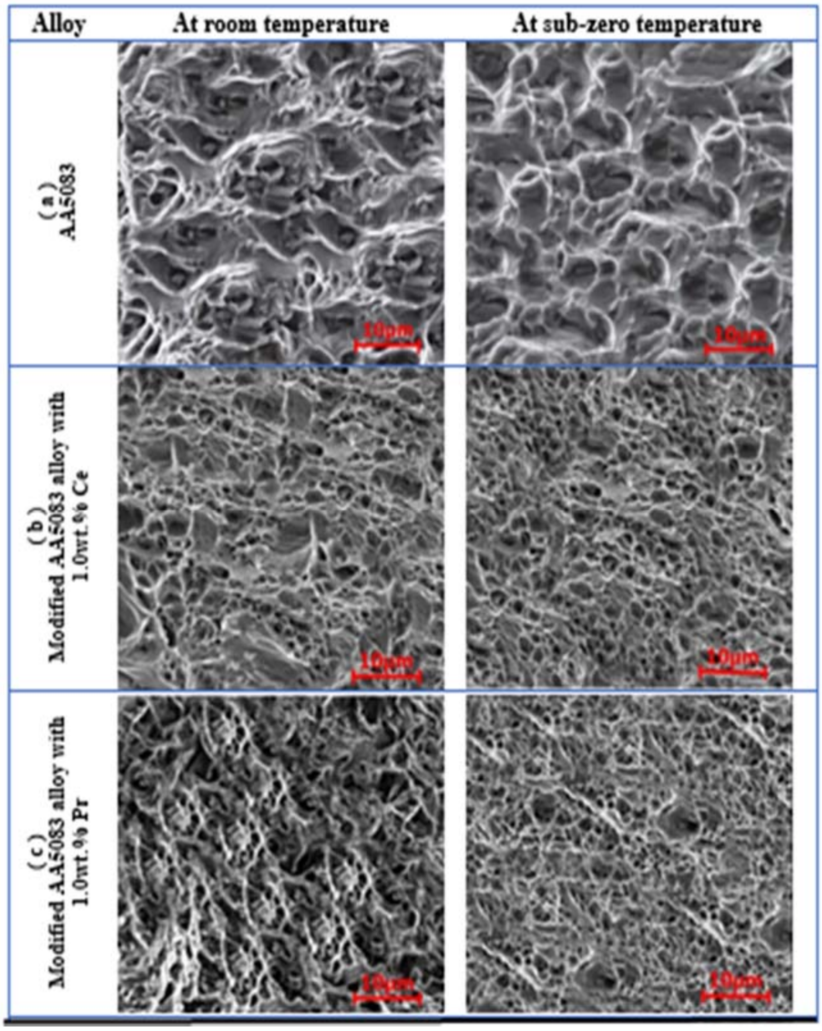

FIG. 4. PV-SEM images fractographs of fracture surfaces of tested samples after impact tests at room temperature and sub-zero temperature (a) AA5083 (b) Modified AA5083 alloys