The Effects of Mould Materials on Microstructure and Mechanical Properties of Cast A356 Alloy

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ABSTRACT

In this study, the effects of mould materials on microstructure and mechanical properties of cast A356 Al alloy were investigated. The alloy was poured into three different moulds. Then the samples were homogenised and applied T6 heat treatment. The optical, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) studies were carried out. Secondary dendrite arm spacing (SDAS) was measured by image analysis systems. Hardness and tensile tests were also performed. The ultimate tensile strength (UTS) values were evaluated by Weibull statistical analysis. As a result of the studies, the highest values of SDAS were measured for the samples obtained using ceramic mould, which led to the slowest cooling rate. The lowest values of SDAS were measured for the samples obtained using chromite sand mould, which led to the highest cooling rate. The hardness values increased about 2.5 times when T6 heat treatment was applied to the samples. The highest tensile strength was observed for the samples obtained by sand mould.

1. Introduction

Al-Si alloys are widely used in various industries, particularly automotive industry due to their excellent castability, good resistance of corrosion, high strength and low density. In automotive industry, various parts like engine block and cylinder head are produced from these alloys [1-7]. However, these cast alloys are not used in the critical structural applications due to the limitation of mechanical properties. Production of these alloys by casting method is of economic attractiveness. Some casting defects occurred during casting process, such as gas pores, shrinkage cavities, oxide films and inclusions, affect the mechanical properties negatively [8, 9]. The mechanical properties of cast Al alloys are also related to chemical composition and varying solidification conditions due to mould materials, core and chiller [10-12]. Mould material, one of the effective mechanical properties of solidification condition, is an important parameter that affects the microstructure. Heat transfer coefficient of the mould material plays an important role in local solidification time and secondary dendrite arm space (SDAS). In conjunction with SDAS, grain size, and the morphology of eutectic silicon (Si) are the other effective parameters on mechanical properties. Aging heat treatment (T6) is applied in order to improve the

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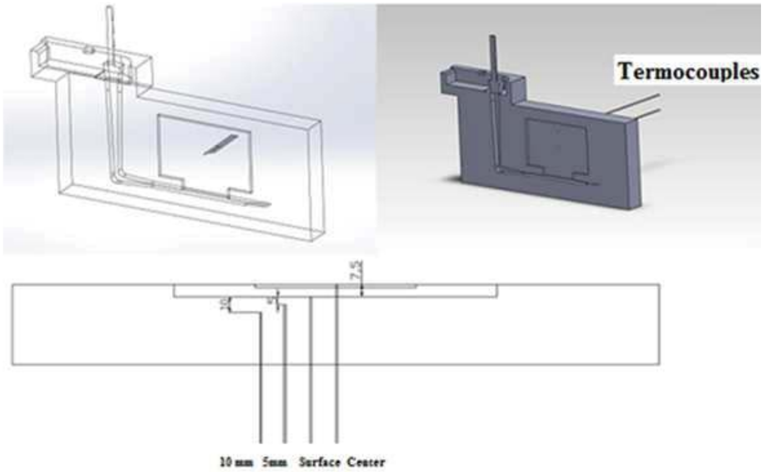


Fig. 1. A schematic view of prepared moulds and thermocouples position in the experimental studies

Table 1. The chemical composition of cast A356 Al alloy

Si	Fe	Cu	Mn	Mg	Zn	Ti	Na	Al
7.07	0.32	0.003	0,032	0.43	0.033	0.113	0.0002	Balance

Mechanical properties of A356[13-17]. In T6 heat treatment, Mg and Si atoms result in fine Mg_2Si intermetallic phases after A356 Al alloy is solution treated at a high temperature above the solvus curve, quenched and aged. In addition, depending on the iron content of the alloy, some intermetallic (β or π) phases also occur in the microstructure during casting process and aging treatment. In this study, the effects of mould materials and cooling rate on the microstructure and mechanical properties of cast A356 Al alloy were investigated. Three different mould materials (quartz, chromite and ceramic) were used in order to obtain different cooling rates.

2. Experimental

In order to determine the effects of mould materials and cooling rate on the microstructure and mechanical properties of A356 Al alloys, three different mould materials (quartz, chromite and ceramic) of different heat transfer coefficients were used. For the quartz mould, AFS 60-65 Quartz(grain fineness number)(SiO_2), and alkali phenolic resin and hardener were used, while for chromite sand moulds, AFS 50-55 (grain fineness number) chromite sand, alkali phenolic resin and hardener were used. For the ceramic mould, Lod607 thermal ceramic material with high thermal shock resistance of up to 1100 ^oC, was mixed with up to 90 % water. After the moulds were prepared, four K type thermocouples, 1 mm in diameter, were placed into different positions of the moulds to obtain cooling curves during casting process as shown in Fig. 1. Cooling rate is calculated using the placed-at-centre thermocouples' data as follows;

$$\text{Cooling rate } (^oC/s) = \frac{\Delta T}{\Delta t} \quad [1]$$

Where ΔT is temperature difference between two temperature points, Δt is time difference between two time points during solidification.

Chemical composition of cast A356 Al alloy is given in Table 1. The melting processes were carried out in an electric resistance furnace with a capacity of 40 Kg. Following the melting process, degassing process was performed by injecting argon gas into the liquid metal for 5 minutes at 1 bar and 750 ^oC in the furnace.

When the melting and degasing processes were completed, the liquid material was cast into the mould at 730 ^oC. A bottom pouring crucible was used in order to prevent the entrance of the slags into the moulds. After the casting process, the thermocouples were removed from the moulds and then the runner systems of cast plates were cut. The cast plates,

Table 2. The calculated cooling rates

Cooling rate ($^{o}C/sn$)	Quartz mould	Chromite sand mould	Ceramic mould
	0,28	0,32	0,19

200x125x15 mm in dimensions, were homogenised for 6 hours at 540 ^{o}C and cooled in the furnace in order to decrease the internal stress and segregations which occurred during solidification. Following the homogenisation heat treatment process, tensile samples were prepared from the plates according to ASTM B557M-10 standard. 5 tensile samples were prepared for each plate. Then aging process was applied to the prepared tensile samples. All the samples were quenched after being solution-treated for 8 hours at 540 ^{o}C. Natural aging process was applied to the quenched saturated solid solution for 24 hours at room temperature and then an artificial aging process was also carried out for 10 hours at 170 ^{o}C. Tensile tests were performed by taking the average of 5 test samples from each plate at a crosshead speed of 2 mm/min using a Shimadzu AG-IS 50 kNunit. The hardness tests were performed by taking the average of 5 samples from each plate through Vickers (HV2) macro hardness measurement using an Affriunit before and after T6 heat treatment. The density measurement was performed by taking the average of 5 samples according to Archimedes' principle and their % porosity ratios were calculated. Standard metallographic processes were applied and the samples were etched with 95 ml H_2O, 2.5 ml HNO_3, 1.5 ml HCl and 1 ml HF (Keller) solution for 15 seconds for microstructural analyses. The samples were examined under an optic microscope and the secondary dendrite arm spacing (SDAS) was measured using MSQ Plus image analyse system. Then the samples were examined by a TESCAN scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS). In addition, fractured surfaces of the tensile samples were examined through SEM. The ultimate tensile strength (UTS) values were evaluated by Weibull statistical analysis.

3. Result and discussion

3. 1. Cooling rate and solidification conditions

Cast A356 Al alloy's mechanical properties are directly related to microstructure of the alloy. For this reason, the solidification time of the alloy is of great importance on the microstructural formation after casting process. The obtained temperature curves are given in Fig. 2, and the calculated cooling rates are given in Table 2.

According to Fig. 2 and Table 2, the highest cooling rate was obtained for the chromite sand mould followed by the quartz and ceramic moulds. In addition, it is inferred from the temperature values that the latest solidification occurred at the centre of the plate. Sebaie reported that heat treatment and cooling rate are effective parameters on the mechanical properties of cast Al-Si alloys [18]. Microstructure changes depending on the cooling rate and solidification condition. The optical microscope images of cast A356 Al alloy samples from different cast mould materials are given in Fig. 3.

3. 2. Microstructure examination

The microstructure of the alloy changes depending on the cooling rate and solidification condition as seen in Fig. 3. The finest grained structure was obtained for the chromite sand mould samples due to its high thermal conductivity. The quartz sand moulded specimens exhibited larger grain than the chromite sand moulded samples and the ceramic moulded samples exhibited the largest grains. It is understood from optical images that the matrix has the form of dendritic α-Al structure, and eutectic silicon particles are found among α-Al dendrites. In addition, some intermetallic compounds and oxide films are observed in the microstructure. It was reported that these intermetallic compounds were also observed in the previous studies [19-21]. In Fig. 4, the SEM and EDS mapping images are given to identify these intermetallic compounds for the quartz sand moulded sample.

It is understood from SEM and EDS mapping images the matrix is Al. Si particles spread randomly and Mg is found to be homogeneous

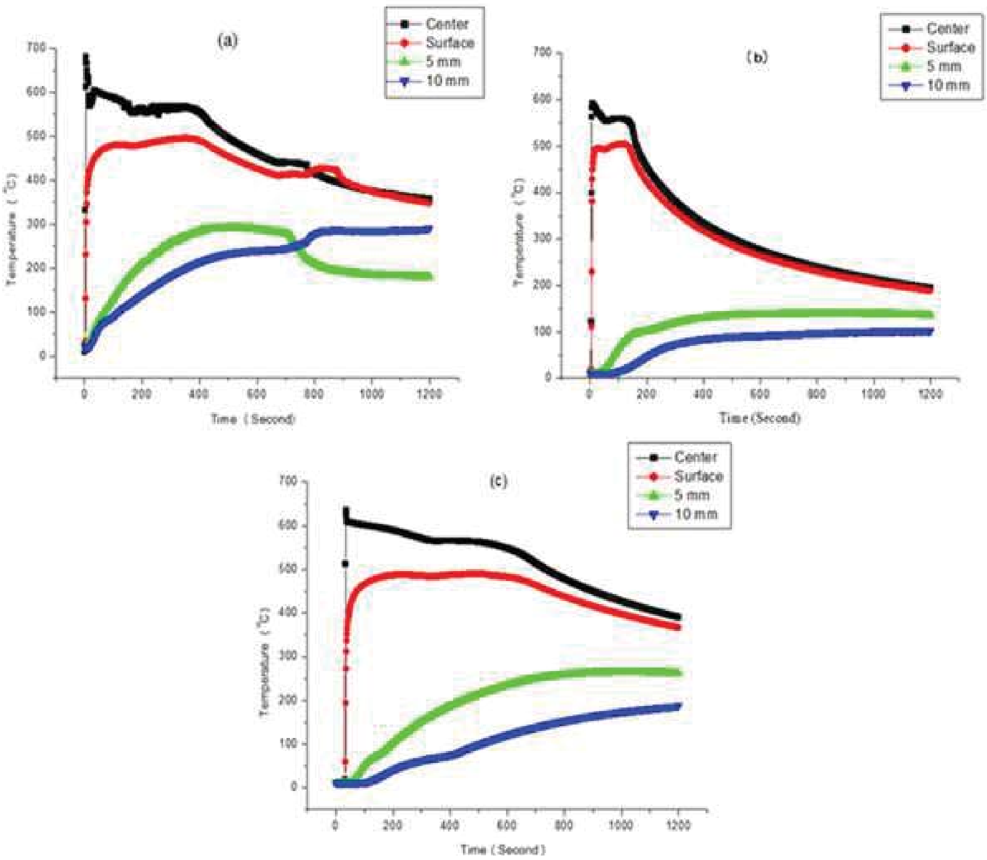


Fig. 2. The temperature values obtained from thermocouples a) quartz sand mould, b) chromite sand mould c) ceramic mould

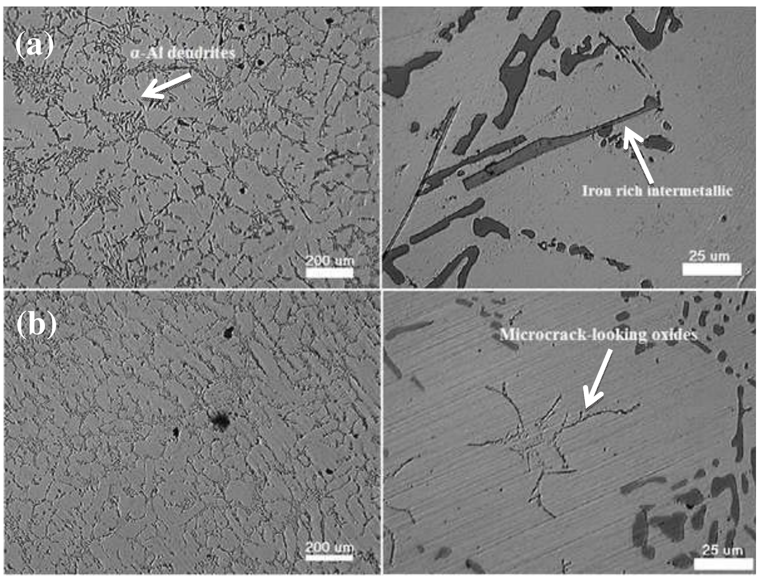
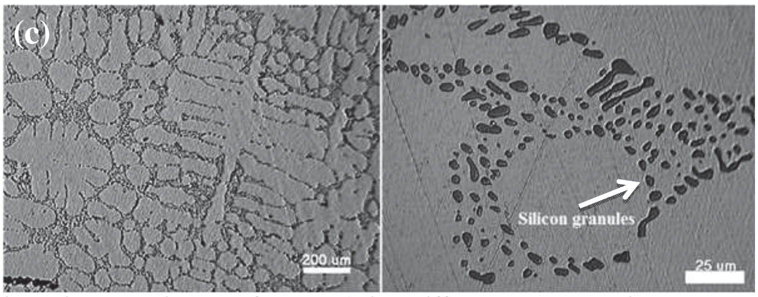


Fig. 3. The optical microscope images of cast A356 into different mould materials a) quartz sand mould b) chromite sand mould, c) ceramic mould



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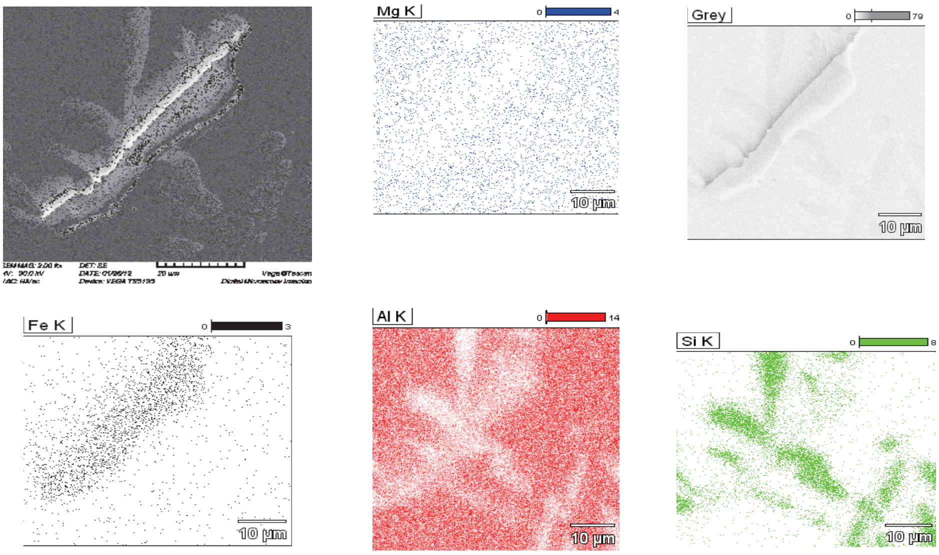

Fig. 4. The SEM and EDS mapping images cast into quartz sand mould.

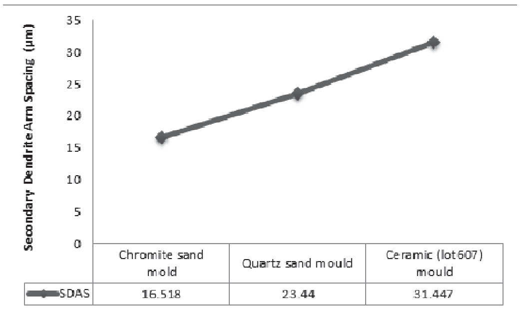

Fig. 5. SDAS values for cast different mould materials

in the matrix. In addition, iron rich intermetallic compound was observed in the structure. This intermetallic compound adversely affects the mechanical behaviour [19-21]. The other important parameter, which affects the mechanical properties, is secondary dendrite arm spacing [3]. The measured SDAS values for the samples moulded using the three different moulds are given in Fig. 5.

It is shown in Fig. 5 that the dendritic structure and SDAS values (about 31 µm) are quite high at slow cooling rates for the samples cast into ceramic mould. For the samples cast into quartz sand mould, SDAS values become about 23 µm.The lowest SDAS values (about 16 µm) are seen for the samples cast into chromite sand mould.

3. 3. Mechanical Properties

The hardness values measured before and after T6 heat treatment are given in Table 3. About 2.5 times increased for T6 heat treated samples are seen from the table. This increase in the

Table 3. The hardness values before and after aging heat treatment.

Mould Material	Hardness Values Before T6	Hardness Values After T6
Quartz mould	44	114
Chromite mould	45	115
Ceramic mould	40	87

Table 4. Density and porosity % values

Mould Material	Density (gr/cm^3)	Porosity (%)
Quartz mould	2,63	1,75
Chromite mould	2,58	3,65
Ceramic mould	2,61	2,46

Table 5. UTS and elongation % values

	UTS (MPa)	Elongation (%)
Quartz sand mould	179	8,24
Chromite sand mould	155	8,94
Ceramic mould	136	5,75

Hardness values are based on Mg_2Si phases precipitated by aging heat treatment [18, 21, 22].

The density and percentage of porosity values of all the samples are given in Table 4. The highest density values are seen for the samples cast into the quartz sand mould. This is followed by the samples cast into the ceramic and chromite moulds. The lowest percentage of porosity values are observed for the samples cast into quartz sand mould. Similar to density values, this is followed by the samples cast into the ceramic and chromite moulds.

The ultimate tensile strength (UTS) and elongation % values of the samples are given in Table 5. As a result of the tensile test, the highest UTS values are observed for the samples cast into the quartz sand mould and this is followed by the ones cast into chromite mould and ceramic mould. The highest UTS values were expected for the samples cast into the chromite sand moulds because of the lowest cooling rate and the least SDAS value, due to the occurred oxides which reduced the UTS, in the microstructure looking like cracks (Fig. 3 b). Depending on the solidification conditions and cooling rate, the elongation values increased with the decrease of SDAS values. Increasing hardness and strength can be explained by the secondary phase precipitates formed with the aging treatment in the microstructure. It is expressed more clearly; A356 Al alloy gains strength by formed Mg_2Si precipitates with aging treatment. Mg_2Si precipitates act as obstacles to dislocation movement and thereby strengthened heat treated alloys.

3. 4. The Weibull Distribution Analysis

Tensile test results were evaluated by Weibull Statistical analysis (Fig. 6). The effect of the cooling rate on ultimate tensile strength (UTS), cast into different mould materials was compared to the Al-Si-Mg alloy.

Weibull Statistical analysis were used in previous studies to determine the effects of oxide formations on quality of cast parts and their mechanical properties [24,25]. For this reason, in order to determine the quality of casting in this study, the tensile test results were evaluated by Weibull distribution. Weibull distribution can be explained as follows:

$$F_W = 1 - \exp\left[-(\frac{x}{\eta})^{\beta}\right] \qquad [2]$$

where, Fw is the cumulative fraction of failures (in a tensile test), x is the variable being measured, i. e. tensile strength, η is the characteristic stress at which 1/e of the specimens survive and β is the parameter quantifying the spread of the distribution, often referred to as the Weibull modulus.

When the Weibull distributions are examined, it is seen that the Weibull module of the

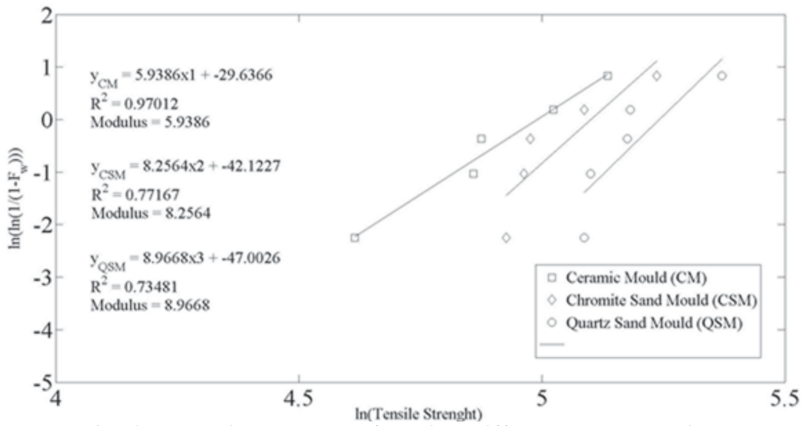

Fig. 6. The Weibull analyse of cast into different mould materials

castinto quartz sand mould samples is 8.96 and their average UTS is 179 MPa. Cast into the chromite sand mould samples' Weibull module is 8.25 and their average UTS is 155 and cast into the ceramic mould samples' Weibull module is 5.93 and their average UTS is 136 MPa. These results suggest that casting quality of poured into the quartz sand mould is better than poured into other moulds. However, it was expected that the casting quality was better poured into the chromite sand mould than others, considering the thermal conductivity of the mould materials before experimental studies. But the Weibull module of cast chromite sand mould is lower than cast into the quartz sand mold, it was considered due to the presence of quasimicrocracks oxide films on the microstructure.

3. 5. Fracture Surface Analysis

The fracture surfaces of the tensile samples' SEM images are given in Fig. 7. As a result of the examinations, on the fracture surface of the samples which were cast into different mould, ductile fracture and massive breakes were observed on each sample surface. More pit and mound was observed on the sample surface cast into the ceramic mould than on the surface of the sample cast into the chromite sand mould in connection with the cooling rate. It shows that these samples fractured more ductile.

In addition, high magnification of SEM images showed that occurred Al-Si eutectic weren't distributed homogeneously by homogenous heat treatment and caused fracture among dendrites.

4. Conclusion

In this study, the effects of solidification and cooling rates on microstructure and mechanical properties of A356 Al alloys which were cast into the moulds with different solidification and cooling rate were investigated. The results obtained in this study are summarized below;

- As a result of casting into the moulds with different solidification and cooling rates, the highest cooling rate was measured on samples which were cast into the chromite sand mould, followed by cast into the quartz sand mould and ceramic mould.
- The highest SDAS values were measured on the sample which was cast into the ceramic moulds with the slowest cooling rate. It was followed by the sample cast into the quartz sand mould chromite sand mould.
- The lowest density values were measured at the samples which were cast into the chromite sand mould. It was followed by the sample cast into the ceramic mould and quartz sand mould.
- The highest porosity % value was calculated at the samples which cast into the chromite sand mould, followed by ceramic mould, and quartz sand mould.
- Hardness values of heat treated (T6) samples increased about 2.5 times. The highest hardness value was measured at the samples which were cast into the quartz sand mould. It was followed by chromite sand mould and ceramic mould.

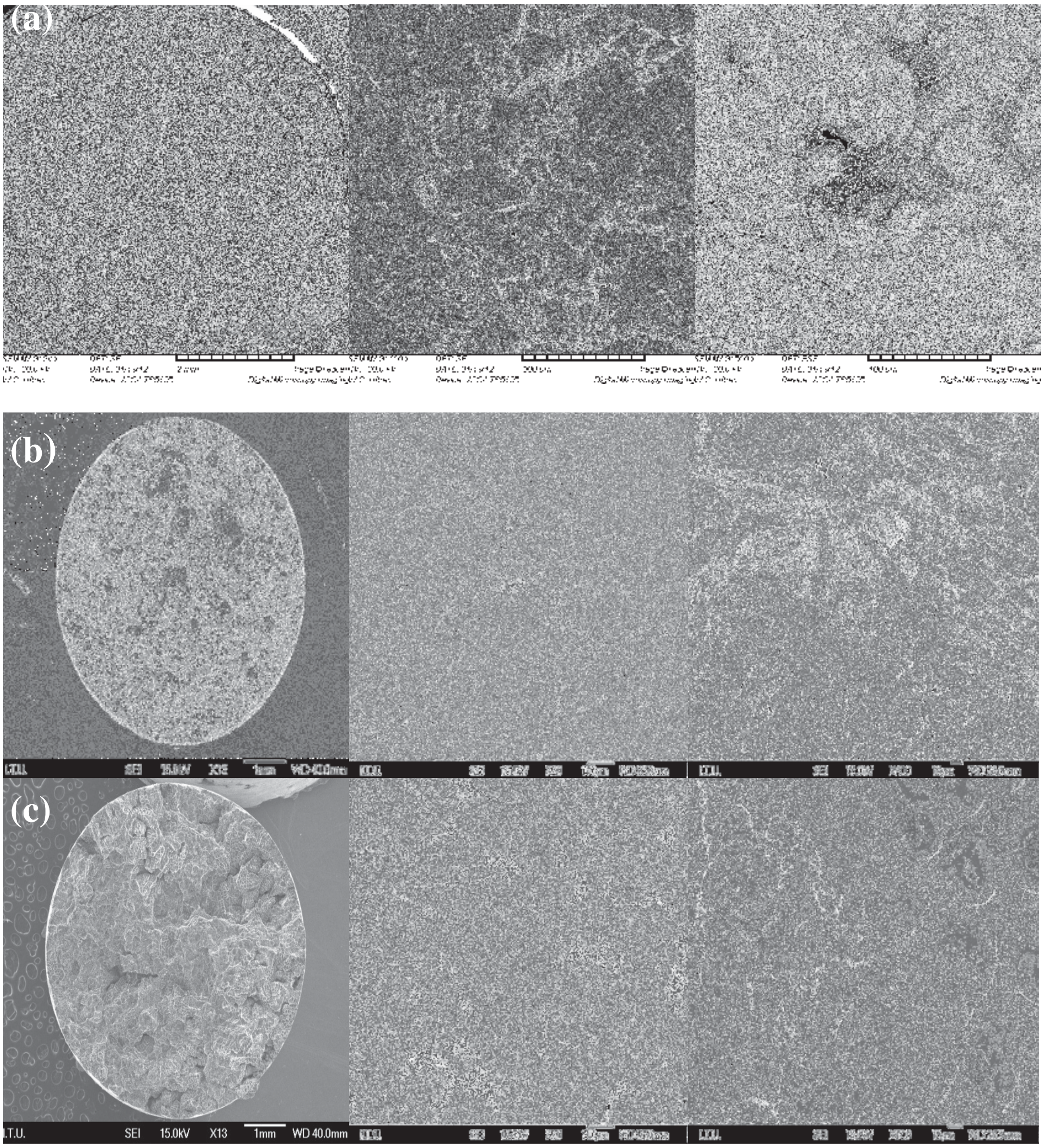

Fig. 7. The SEM images of fracture surface; a) quartz sand mould, b) chromite sand mould c) ceramic mould

- The highest UTS values were obtained at the samples which were cast into quartz sand mould; it was followed by chromite sand mould and ceramic mould. The highest elongation % values were obtained at the samples which were cast into the chromite sand mould; it was followed by quartz sand mould and ceramic mould sand.
- At the Weibull analysis using UTS values, the highest Weibull module is calculated at the samples which was cast into the quartz sand mould, followed by chromite sand mould and ceramic mould.

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