

## **THERMAL FATIGUE RESISTANCES OF 356 AND 413 CAST AL ALLOYS**

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**Date of Receive: July 2008      Date of Acceptance: September 2008**

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**Abstract:** *Thermal fatigue is a stochastic process often showing considerable scatter even in controlled environments. Due to complexity of thermal fatigue, there is no a complete analytical solution for predicting the effect of this property on the life of various components, subjected to severe thermal fluctuations. Among these components, one can mention car cylinder, cylinder head and piston which bear damages due to thermal fatigue. All these components are usually produced by casting techniques. In order to comprehend and compare the thermal fatigue resistance of cast Al alloys 356 and 413, this research was designed and performed. For this purpose, several samples in the form of disc were cast from the two alloys in sand mould. The microstructures of the cast samples were studied by light microscopy in order to choose the samples with the least amounts of defects for thermal fatigue tests. The results of thermal fatigue tests showed that the nucleation of microcracks in Al-356 alloy occurred at shorter time relative to those occurred in Al-413 alloy under the same test conditions. In addition, the density of micro-cracks in Al-356 alloy was more than that of Al-413 alloy. The results of fractography on 356 alloy indicated that the cracks were generally nucleated from inter-dendritic shrinkage porosities and occasionally from the interface of silicon particles with the matrix. The growth of these micro cracks was along the dendrite arms. Fractography of 413 alloy fracture surfaces showed that nucleation of microcracks was often associated with silicon particles.*

**Keywords:** *Thermal Fatigue, Inter-Dendritic Fracture, Silicon Particles, Al-Alloy, Microcracks, Al 356, Al 413.*

### **1. INTRODUCTION**

Thermal fatigue is by definition a process of nucleation and subsequent gradual development of damage in components exposed to cyclic temperature changes [1]. This type of fatigue which is related to rapid increase and decrease in operational temperature is a class of low cycle fatigue that results to failure, usually occur at less than 50,000 cycles [2, 3].

This type of fatigue causes non-uniform dimensional changes in materials and consequently leads to distortion or fracture of the materials. The problem of crack formation and growth in some car components such as cylinder heads due to fluctuation in mechanical or thermal conditions is difficult to be predicted as it depends on a number of influencing parameters and the complexity of material behaviour under such changing conditions. This type of fatigue is said to be responsible for most

of the damages occur in car piston and casting moulds under pressure [4, 5].

Among Al-Si alloy which are used in very wide scale for production of car motor components are Al-413 for manufacturing of piston and Al-356 for cylinder and cylinder head. In contrast with steels, by increasing the strength of these type of Al alloys, their fatigue properties do not increase, therefore, for obtaining suitable fatigue strength in Al alloys some certain thermo-mechanical operations should be performed [6]. Stolarz et al. [7] in their study on thermal fatigue of Al alloys, stated that thermal fatigue resistance of Al alloys is related to Si morphology, dendrite arm spacing (DAS), the amount of porosity, composition, and heat treatment of these alloys. Therefore they suggested that by modifying the silicon structure in Al-Si alloys one can get shorter DAS and lower porosity, thus increase fatigue resistance of these type of alloys. Reducing grain size also

increases tensile and fatigue strength at lower temperature, but decreases these properties due to occurrence of creep at high temperatures, according to Stolarz et al [7]. In this research, the thermal fatigue resistance of cast Al alloys 356 and 413 has been studied and compared.

## 2. PRACTICAL WORKS

The dimensions of the cast samples are shown in Fig. 1 (a) and Schematic of the sand mould used for casting the thermal fatigue specimens is shown in Fig. 1(b). The mould consisted of silica sand and Sodium Silicate adhesive. For melting the original charge, resistant furnace and for degasification, Argon gas was utilized at 740°C. Casting defects were studied by radiography and scanning electron microscopy (SEM) techniques. Quantitative metallography for measuring the mean volume fraction of the defects was performed, using an image analyzer on at least

50 images taken from various sections of each alloy. The mean values of the five largest pores for each alloy, quoted as the mean pore size, are shown together with the samples codes in Table 1. Specimens for thermal fatigue tests with dimensions shown in Fig. 1(a) were machined from the cast bars. The samples were ground with various emery papers up to grade 1000 and then polished for obtaining smooth surfaces. Thermal fatigue tests were performed in a resistance furnace.

The specimens heated for a period of 30 sec. at 250°C and then quenched in 25 °C water. This treatment was repeated for 500 cycles. The surfaces of the specimens were examined by light microscopy after every 50 cycles for detecting the possible nucleation and evaluating, the numbers and the sizes of the surface cracks. The fracture surfaces of the ruptured specimens were examined by SEM technique.

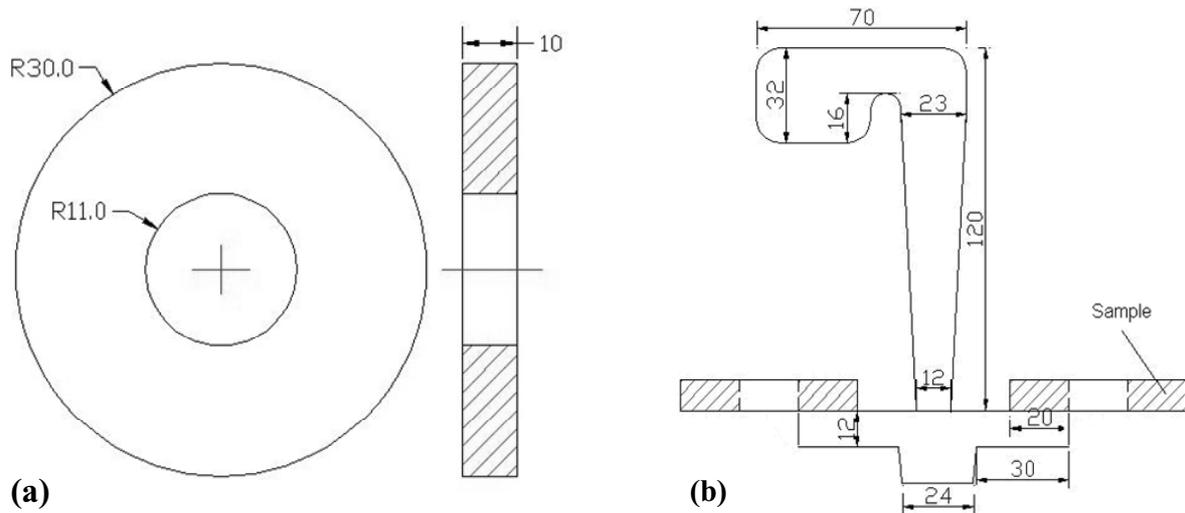


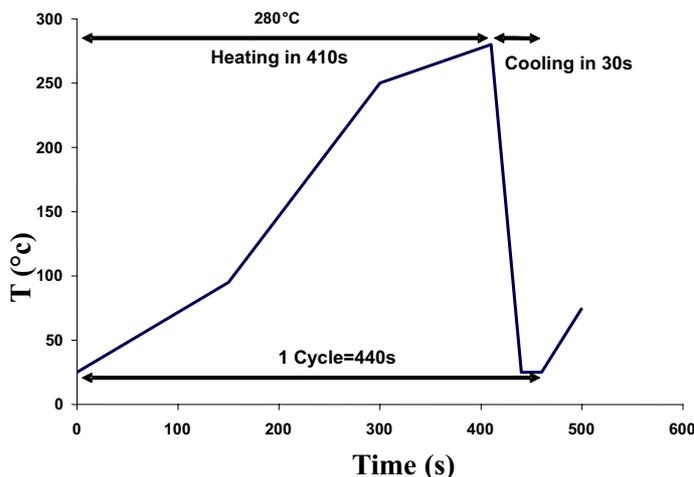
FIG. 1. Schematic of (a) fatigue specimens and (b) sand mould used All dimensions in mm.

Table 1. Samples codes and mean pore size.

Al alloy	Code	Mean pore size , $\mu\text{m}$
356	3A	80
356	3B	120
413	4A	150
413	4B	130

**TABLE 2.** Mean chemical compositions of Al-356 and Al-413 alloys, wt%.

Element		Si	Fe	Cu	Mn	Mg	Al
Wt%	Al-356	5.985	0.351	0.132	0.007	0.287	Bal.
	Al-413	11.216	0.383	1.054	0.008	0.004	Bal.



**Fig. 2.** Thermal cycle used for fatigue tests.

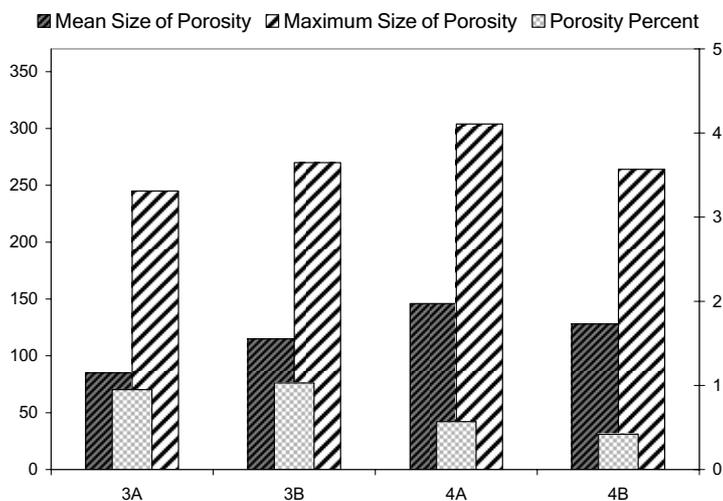
### 3. RESULTS AND DISCUSSION

The mean chemical compositions of the cast Al alloys used in this research are presented in Table 2, and the thermal cycles used for the fatigue test is shown in Fig. 2

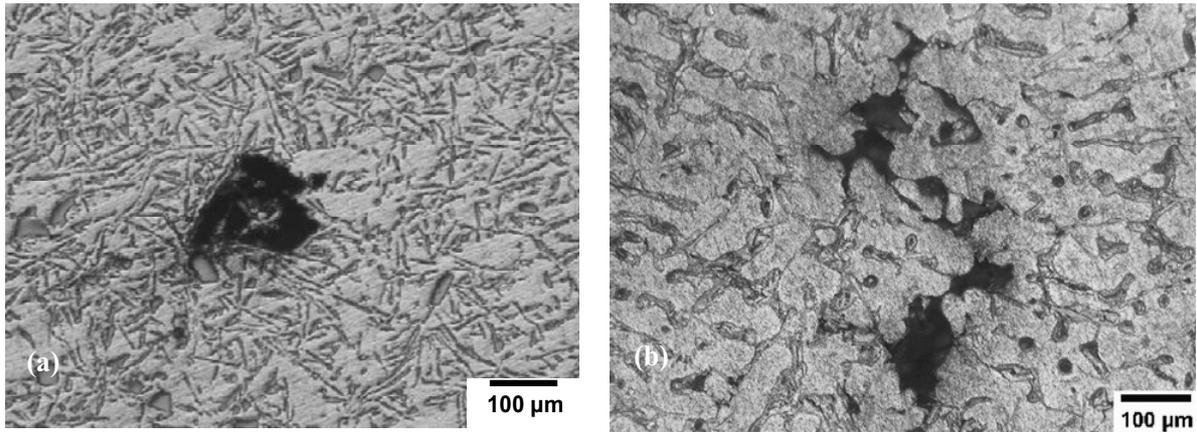
The quantitative results of pore sizes in various samples are presented in the form of a bar chart in Fig. 3.

This figure shows that the total percentages of

porosities in both samples of the alloy Al-356 (i.e.3A and 3B) are more than those of the alloy Al- 413. However, the mean size of the five largest pores in alloy Al-413 (i.e. 4A) is slightly more than that of alloy Al- 356 as it can be seen in Fig. 3. Considering that the alloy Al-413 is a eutectic type alloy, as shown in Fig. 4, one expects that the amount of its total shrinkage porosity should be lower than the alloy Al-356, as it has been stated by McDowell et al. [8].

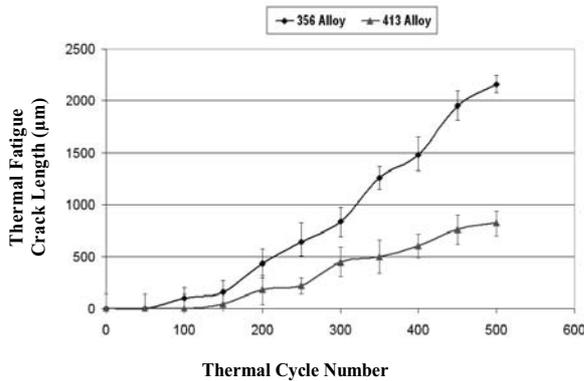


**Fig. 3.** Sizes and percentages of porosities within various samples.



**Fig. 4.** Shrinkage porosity within (a) Al-413 alloy and (b) Al-356 alloy. Eutectic type of microstructure in (a) and dendrite type in (b) should be noticed.

The pores observed in the microstructure of the alloy Al-356, Fig. 4(a) were basically of shrinkage type, while the pores in the alloy Al-413 were both shrinkage and of gas types. Figs. 5 and 6 show the results of quantitative metallography in the surfaces of the samples, subjected to thermal fatigue tests.

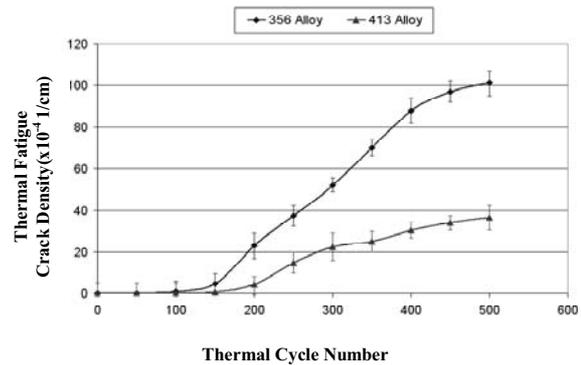


**Fig. 5.** Variation of thermal fatigue crack size as a function of the number of thermal cycle.

Fig. 5 indicates that up to about 70 cycles no crack was initiated in the surface of 356 alloys, while for the alloy 413 up to about 140 cycles crack initiation was not observed in the surface. In addition, the rate of crack formation and growth in the alloy 356 were more than those in the alloy 413 as indicated by the sharper slopes of curves shown in Figs. 5 and 6. These figures also show that the average crack size and density for any cycle in alloy 356 are more than those of the alloy 413. It seems that the irregular and sharp edges of shrinkage pores in the alloy 356 were very suitable sites for crack nucleation, as shown in Fig. 7.

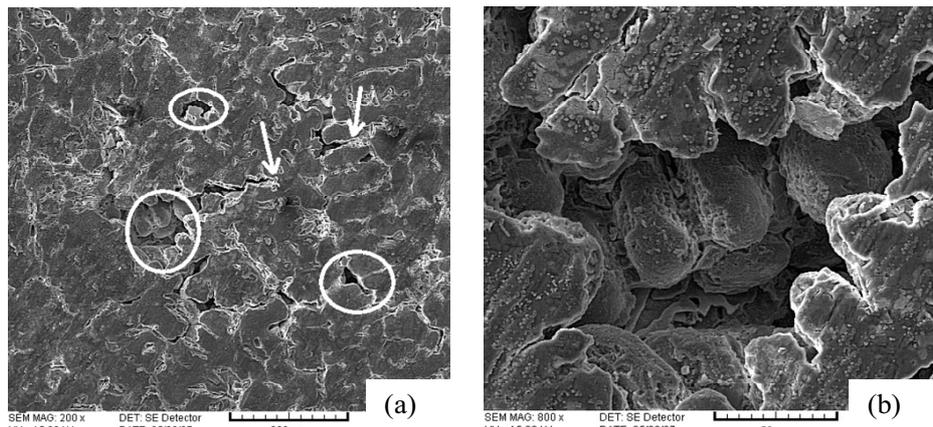
Investigating the surface of the samples after

every 50 cycles up to 500 cycles indicated that most of the thermal fatigue cracks in the alloy 356 started from the surface interdendritic pores (Figs 7-9), while in the 413 alloy most of the cracks started from the ruptured silicon particles, Fig. 10.

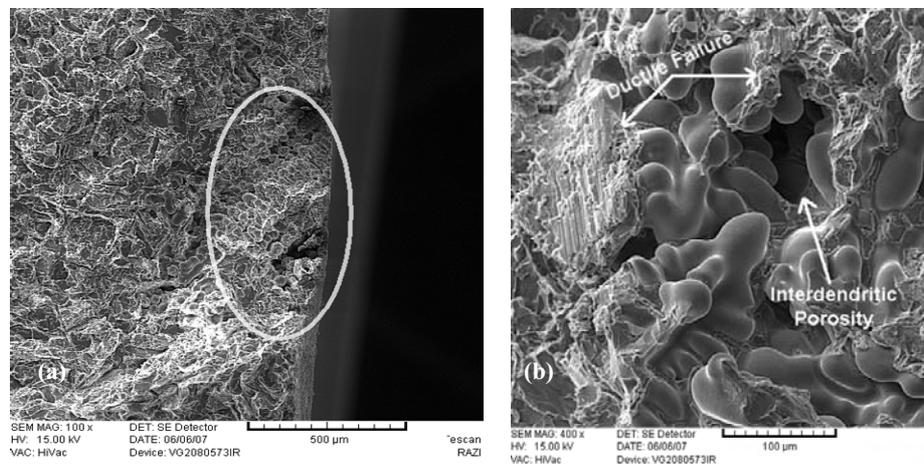


**Fig. 6.** Variation of thermal fatigue crack densities as a function of the number of thermal cycle.

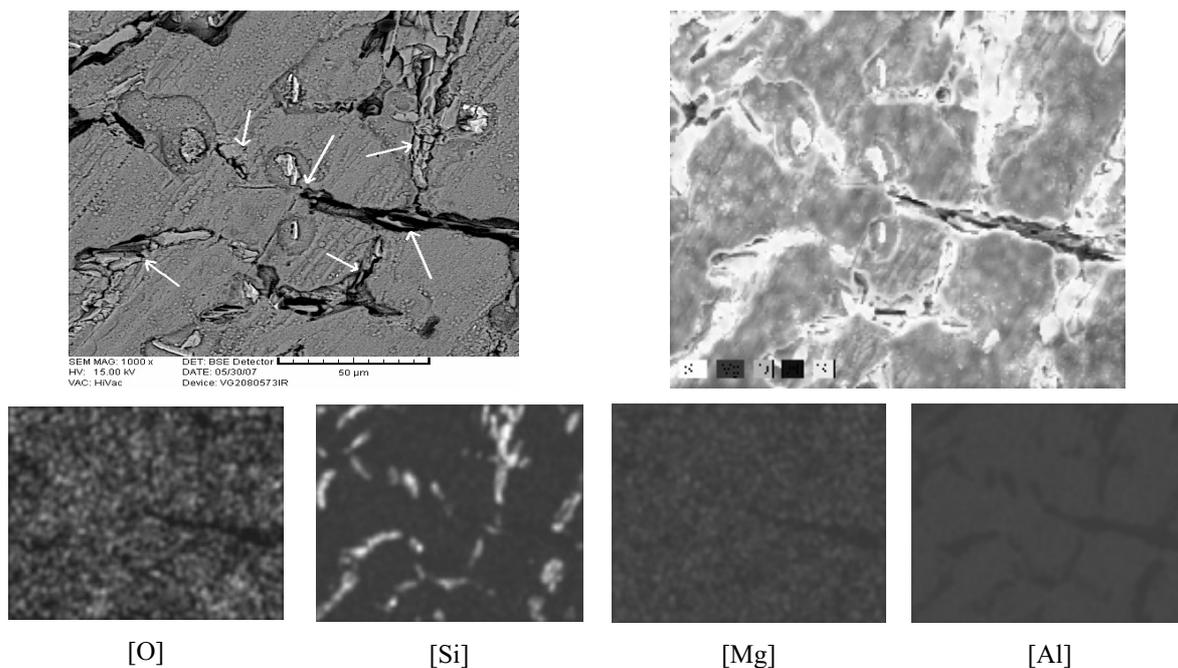
One should notice that since the nucleation sites of the cracks in 356 alloy mostly started from shrinkage pores, and also since the amounts of the total shrinkage porosity in this alloy was more than that of 413 alloy, one expects that the number of suitable sites for thermal fatigue crack initiation in 356 alloy be more than that of 413 alloy. This seems to be the reason of higher crack density in Al-356 alloy relative to Al-413 alloy. On the other hand, higher concentration of fatigue cracks in the surfaces of 356 alloys can cause higher concentration of stress within its surface particularly in tension part of the cycle; hence one can claim crack initiation in Al-356 alloy is very sensitive to concentration of shrinkage porosity particularly those located within the surface.



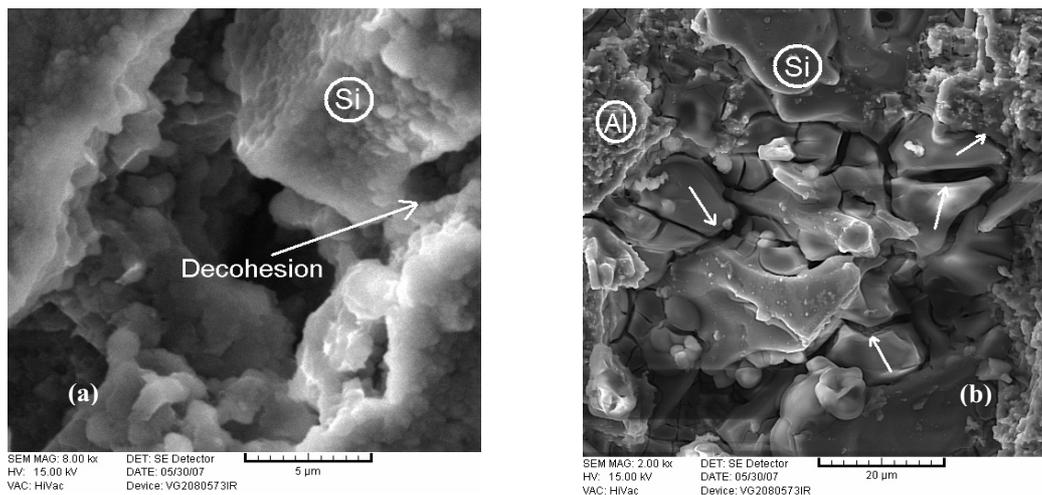
**Fig. 7.** SEM macrographs from (a) surface interdendritic cracks of Al-356 alloy (b) larger magnification of a selected crack in (a).



**Fig. 8.** SEM micrographs of ruptured surface of an Al-356 alloy (a) general view (b) secondary crack site within the interdendritic porosity.



**Fig. 9.** Some typical crack initiation sites in Al-356 alloy together with X-Ray maps of elements on a transverse section under fractured surface.



**Fig. 10.** Typical SEM micrographs of crack initiation sites in Al-413 alloy (a) decohesion of interface between matrix and Si particle was the nucleation site (b) broken Si particle provided nucleation site.

In Al-356 alloy, as mentioned earlier, cracks started occasionally from the interface of Si particles within the matrix or from the fractured Si particles, as shown in Fig. 9. Considering that the thermal expansion of Al is eight times more than that of Si [9] (Table 3) it is logical to expect that at higher temperature a larger tensile stress is generated at Si particles interface with the matrix which later causes decohesion of these particle from the matrix. Furthermore, due to the fact that the strength of those particles reduces at higher temperature, these particles started to fracture during tensile part of thermal fatigue cycles, so that a suitable sites for crack nucleation within the matrix were then formed.

**Table 3.** Thermal properties of Al and Si [9].

Element	Thermal Expansion Factor ( $\mu\text{m/m.k}$ )	Thermal Conductivity (W/m)
Al	24.5	230
Si	3.2	82

As it has been mentioned before, cracks were either initiated from the fractured Si particles during thermal fatigue of 413 alloy, Fig.10b, or from the interfaces of these particles with the matrix, Fig. 10a, therefore, one can say that crack formation in this alloy was not basically sensitive to internal porosities. Prasad et al [10] reported that when the secondary hard phases are large and rough, the possibility of their fracture or decohesion from the matrix during expansion and contraction is high. Therefore, since the mean size of Si particles observed in Al-413 alloy was larger than that of Al-356 alloy, one

may relate the nucleation of crack observed in this alloy to the large sizes of their hard Si particles. Other factors affecting thermal fatigue resistance of materials are thermal expansion coefficients, specific heat and heat conduction. These properties, for Al alloy 356 and 413 are given in Table 4 [11].

**Table 4.** Thermal properties of Al-356 and Al-413 alloys [11].

Alloy	Mean Thermal Expansion Factor ( $\mu\text{m/m.k}$ )	Thermal Conductivity (W/m)	Specific Heat (J/Kg)
Al-356	21.6	155	963
Al-413	20.5	151	963

#### 4. CONCLUSIONS

The conclusions made from this research can be summarized as follow;

1. Volume percentage of porosities in Al-356 dendritic type alloy was more than that of Al-413 eutectic type alloy.
2. In Al-356 alloy only shrinkage type pores were observed, but in Al-413 alloy generally gas type and occasionally shrinkage pores were seen.
3. The number of cycles required for thermal fatigue crack nucleation in Al-356 alloy was about 70, where for Al-413 alloy this was about 140 cycles.
4. Rates of crack formation and growth in Al-356 alloy were much more than those in Al-

413 alloy.

5. In Al-356 alloy cracks initiated generally from the surface shrinkage porosities, while in Al-413 alloy cracks nucleated from both broken Si particles and decohesion of this particles from the matrix.

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