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EFFECTS OF POROSITY ON MECHANICAL PROPERTIES OF METAL MATRIX COMPOSITE: AN OVERVIEW

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Abstract. Porosity in cast metal matrix composite (MMC) has been known as a defect affecting the enhancement of strength, particularly in particle-reinforced MMC. From previous reviews, among the causes of porosity formation are air bubbles entering the melt matrix material, water vapour on the particles surfaces, gas entrapment during mixing process, evolution of hydrogen, and shrinkage during solidification. Many studies had revealed that casting parameters are the main factors affecting porosity formation. Optimum properties of cast MMC are attained with least porosity content. Generally, increasing content of porosity will decrease the mechanical properties of MMC such as tensile strength, Young's modulus, Poisson ratio, and damping capacity. The presence of porosity decreased the mechanical properties of cast MMC as the failure process is initiated from the voids formed.

Keywords: Porosity, stir casting, mechanical properties, cast metal matrix composite, silicon carbide particle

Abstrak. Keliangan di dalam tuangan komposit matriks logam (KML) adalah satu kecacatan yang boleh mempengaruhi kekuatan bahan terutamanya di dalam KML bertetulang partikel. Merujuk kepada kajian lepas, faktor-faktor pembentukan keliangan adalah berpunca daripada gelembung-gelembung udara yang memasuki leburan matriks logam, wap air yang terdapat pada permukaan partikel, gas yang terperangkap semasa proses pencampuran, evolusi hidrogen, dan pengecutan tuangan semasa pemejalan. Namun, kebanyakan kajian menunjukkan punca utama pembentukan keliangan adalah parameter proses tuangan. Kandungan keliangan yang paling minima akan menentukan sifat optimum tuangan KML. Secara umumnya, peningkatan kandungan keliangan akan mengurangkan sifat mekanikal KML seperti kekuatan tegangan, modulus Young, nisbah Poisson dan muatan redaman. Kesan pengurangan ini berlaku disebabkan oleh proses kegagalan yang berpunca daripada kehadiran lompang keliangan.

Kata kunci: Keliangan, tuangan kacau, sifat mekanikal, tuangan komposit matriks logam, silikon karbida

1.0 INTRODUCTION

Metal matrix composite (MMC) is a material which consists of metal alloys reinforced with continuous fibres, whiskers, or particulates. In order to combine the desirable attributes of metals and ceramics, MMC were designed. MMC produces a material

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whose mechanical properties are an intermediate between matrix alloy and ceramic reinforcement [1]. It has many advantages, which includes high mechanical strength, toughness at elevated temperature, low density, and higher stiffness, compared with matrix alloys. Furthermore, its ability to withstand higher tensile and compressive stresses by transferring and distributing the applied load from the ductile matrix to the reinforcement material has enabled MMC for a wide range of applications as shown in Table 1.

Table 1 Some applications of MMC [1]

Industrial sector	Applications
Aerospace	struts, antennae.
Automobile	piston crowns, engine block.
Electrical	superconductors, contacts, filaments, electrodes.

Interest on MMC has started in 1960s, which initiated from continuous reinforcement material (e.g. tungsten and boron fibres) and aluminium or copper as the matrix element. Somehow in the 1980s, the expansion of MMC production has led to the development of discontinuously reinforced MMC [2]. In the discontinuously reinforced MMC system, mechanical failure processes occur mainly by the formation and bonding of porosity within the matrix [3]. This paper reviews the porosity formation in particulate Al-based MMC and its effects on the mechanical properties.

2.0 BACKGROUND OF THE STUDY

Stir casting method is a relatively low cost liquid processing present to produce MMC and hence, this processing technique had been utilized in this study. Besides being simple, flexible, and attractive, as compared with other techniques, it also allows very large size components to be fabricated and is also applicable to large quantity production. Stir casting route also ensures that undamaged reinforcement materials are attained. Moreover, this type of processing is now in commercial use for particulate Al-based composites [4] and the material produced is suitable for further operations, such as pressure die-casting [5]. There are several difficulties [6] in stir casting that are of concern, which are:

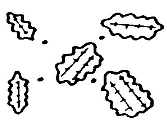
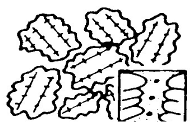
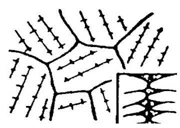
(i) porosity in the cast MMC,
(ii) difficulty in achieving a uniform distribution of the reinforcement material,
(iii) wettability between the two main substances, and
(iv) chemical reactions between the reinforcement material and matrix alloy.

The modified approach of stir casting, however, has improved particularly on eliminating most of the porosity caused by casting parameters [7]. In spite of that, there is no way to avoid porosity. Furthermore, from several observations, there is at least microporosity present at volume fraction of up to 0.07. Heating up both substances simultaneously helps to remove water vapour on the particles surface and also avoid air bubbles from entering the slurry as an air envelope to the reinforcement particles. Besides, the crucible used in this method enables bottom pouring of the slurry, which is most likely to prevent gas entrapment and oxides formed at the melt surface from being casted.

3.0 POROSITY FORMATION

Porosity is a defect formed by interfacial reactions, which causes a decrease in the mechanical properties of MMC. In the metallographic studies, pores are classified into four types: round pores, long and broad pores, long and fissured pores, and small, fissured pores [8]. Table 2 indicates the development and characteristics of the pores formed in the casting. Porosity formation [7] is caused by:

Table 2 Four different types of pores, their development, and characterization in the solidifying casting for the case Al-7Si-Mg [8]

Types of pores	**Round pores**	**Long, broad pores**	**Long, fissured pores**	**Small, fissured pores**
Solidification process and bubble formation.	 Bubbles formation in liquids			
Pore morphology in the structure.				
Characterization:	- Precipitation in the liquid melt or in the beginning of solidification. - Unrestricted bubble growth. - High H_2 concentration required.	- Bubble formation with still high liquid fraction. - Arrangement between growing bubbles and dendrites. - High to medium H_2 concentration.	- Bubble formation during formation of the dendrite network. - Bubble expansion limited by still open melt channels. - Medium to low H_2 concentration.	- Precipitation shortly before the end of solidification. - Shape and size of pores determined by closed interdendritic spaces. - Low H_2 concentration.

(i) gas entrapment during vigorous stirring,
(ii) air bubbles entering the slurry either independently or as an air envelope to the reinforcement particles,
(iii) water vapour (H_2O) on the surface of the particles,
(iv) hydrogen evolution, and
(v) shrinkage during solidification.

These causes are practically affected by the casting route applied [6,9], process parameters which consist of holding time, position of impeller and stirring speed [9,10], and the volume fraction of the reinforcement material in MMC [7].

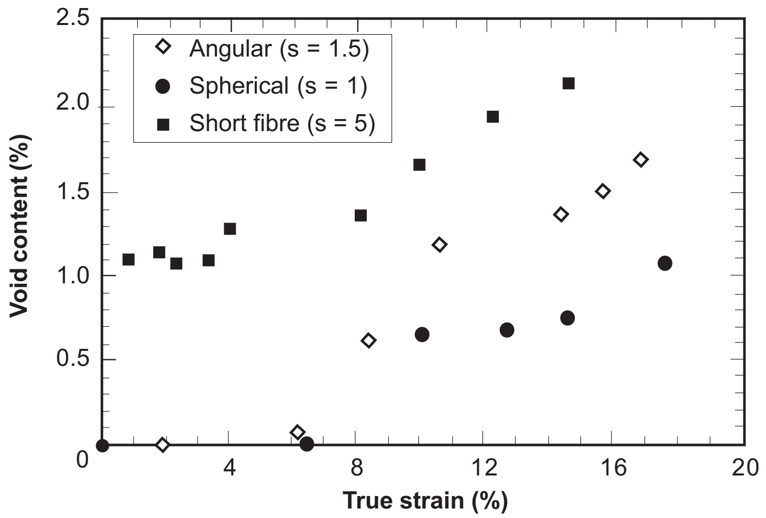


Figure 1 Void content as a function of tensile strain for composites containing three types of Al_2O_3 reinforcements of a volume fraction of 10% [12]

From overall porosity measurement, the porosity content increases with increasing particle size, aspect ratio (Figure 1) [11], and volume fraction of reinforcement material [7] (Figure 2), whereas, increasing the holding time will decrease the porosity level. This was compared between samples cast in steel and graphite moulds, with smaller size of ingots. Producing samples using steel mould has been observed to decrease the porosity content compared with graphite mould (Figure 3). Steel mould influences the cooling rate of the ingot. A faster cooling rate tends to distribute the reinforcement material uniformly as well as decreasing the possibility of porosity formation, which is most likely to develop during solidification (Figures 4 and 5).

Operating stirring process with a high velocity will form a vortex on the surface of the slurry. The development of the vortex is observed to be helpful for transferring the particles into the matrix melt as the pressure difference between the inner and the

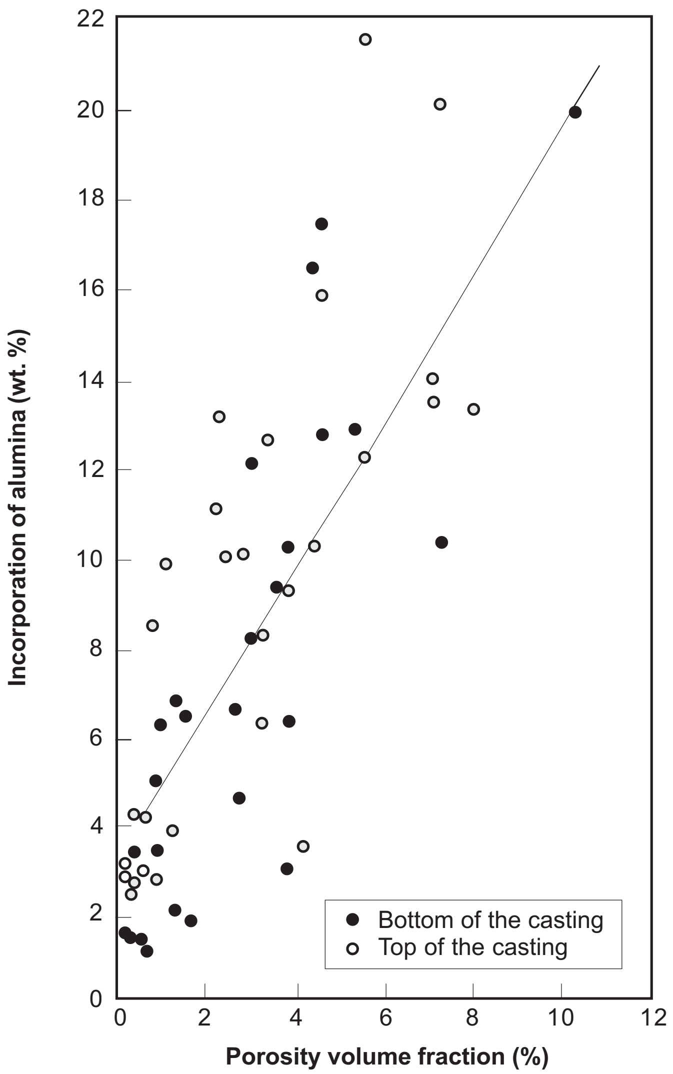


Figure 2 Variation of porosity, with alumina content in cast Al-Al_2O_3 composites [13]

outer surface of the melt sucks the particles into the liquid. This will cause porosity formation in the slurry, as shown in Figure 6. Line A is the original level of the slurry before the stirring process and line B represents the surface observed during stirring, while line C is the final level when the stirring stopped. The level of difference between line A and C is due to gas trapped into the melt by the vortex.

Oxygen and hydrogen are the sources of water vapour presence on the particles surfaces. Along with water vapour, surfaces of $SiC_{(p)}$ are frequently covered with SiO_2 layer [15]. Such layer originates during the SiC production process [16]. Like some metals and ceramics, SiC has an attractive oxidation behaviour. Below a temperature

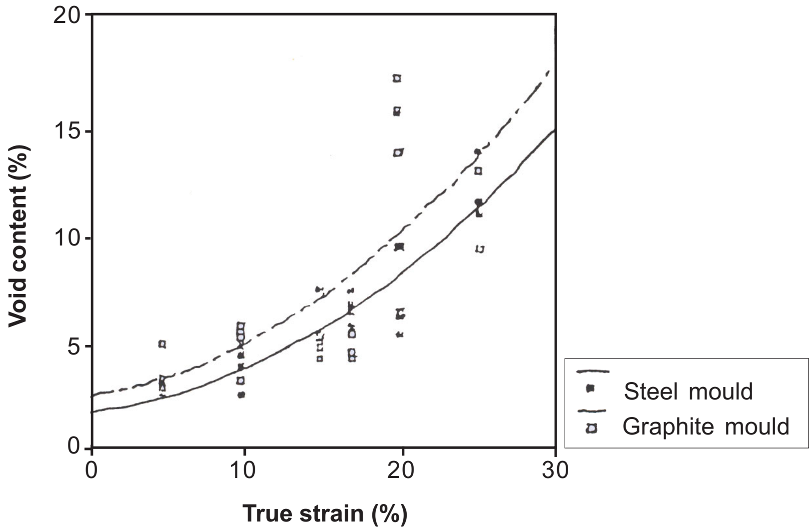


Figure 3 Porosity as a function of SiC content [7]

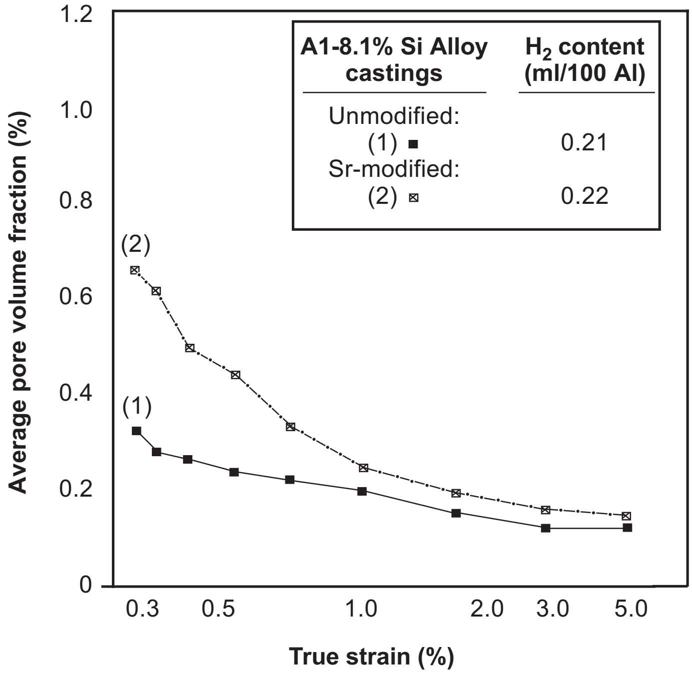


Figure 4 Average pore volume fraction as a function of average cooling rate for Al-8.1 wt % Si alloy cast [14]

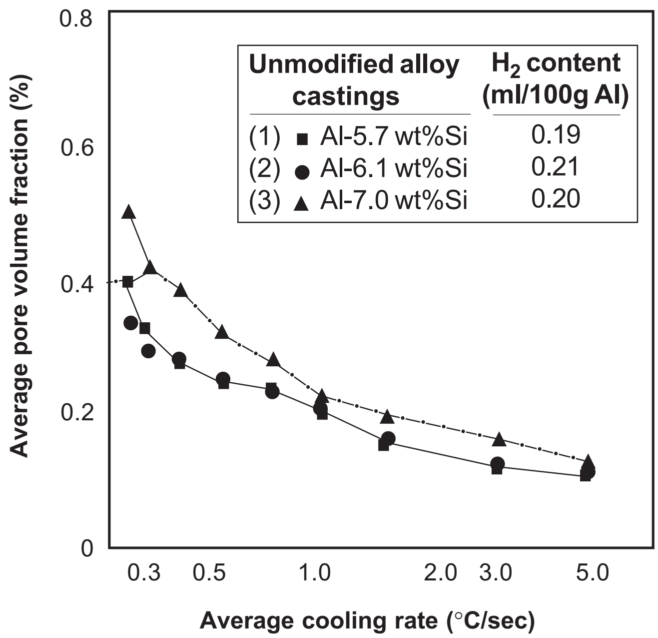


Figure 5 Average pore volume fraction as a function of average cooling rate for alloys with silicon contents of 5.7%, 7%, and 8.1 wt % [14]

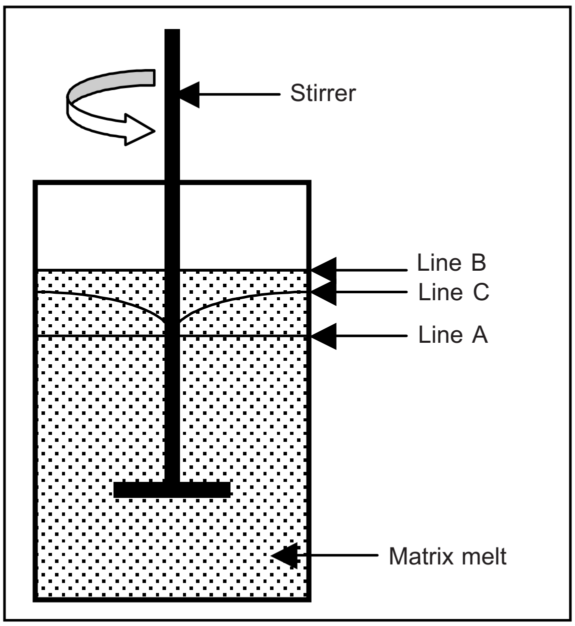


Figure 6 The effects of vortex formation on the surface of a matrix melt [4]

of ~1200°C and with plenty of oxygen, as in air, SiC undergoes passive oxidation in which, a stable SiO_2 film forms, according to the following reaction:

$$2\ SiC + 3\ O_2 \rightarrow 2\ SiO_2 + 2\ CO_{(gas)} \quad (1)$$

In aluminium casting, hydrogen is responsible for gas porosity which penetrates the liquid alloy by the reaction of the aluminium with water vapour [15].

$$H_2O(v) + \frac{2}{3}Al \rightarrow \frac{1}{3}Al_2O_3 + 2H(\text{in Al}) \quad (2)$$

When aluminium solidifies, the hydrogen trapped in the solid metal forms bubbles that produce gas porosity. Referring to Figure 7, as the temperature decreases, the gas solubility decreases. However, the common alloying elements (e.g. Si and Cu) usually decrease the solubility of hydrogen (Table 3). From Sievert's Law, the amount of gas that can be dissolved in a molten metal is given by [15]:

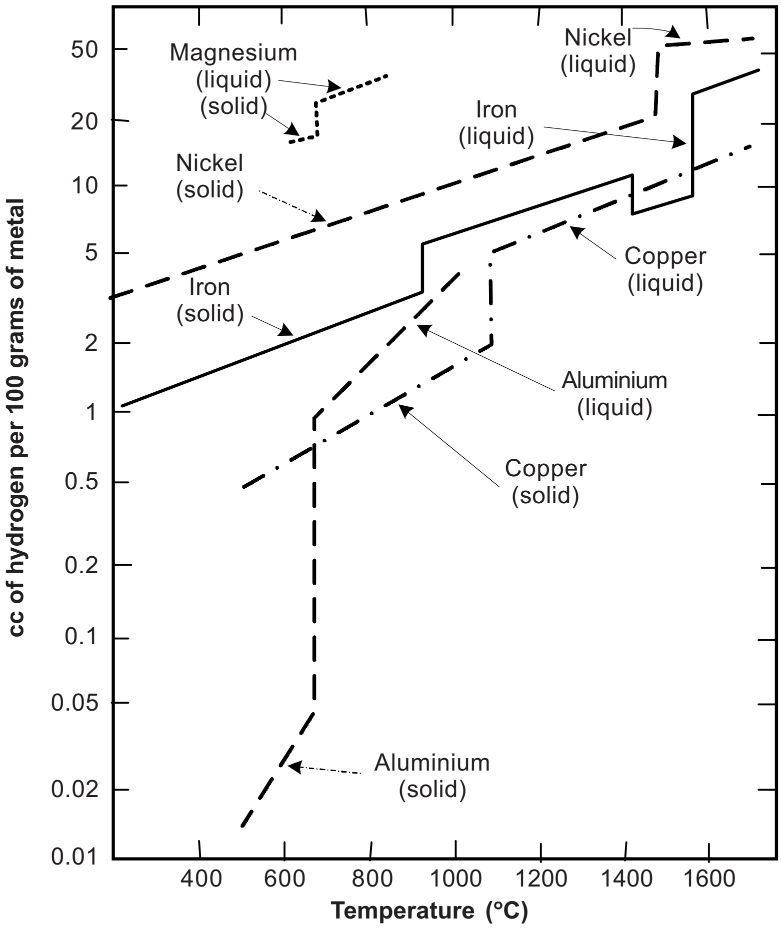


Figure 7 Solubility of hydrogen in metals [17]

Table 3 The solubility of hydrogen in aluminium and its alloys [18]

Alloy	Hydrogen solubility, ppm
Pure aluminium	1.20
Al-7Si-0.3Mg	0.81
Al-4.5Cu	0.88
Al-6Si-3.5Cu	0.67
Al-4Mg-2Si	1.15

$$\%\ \text{gas} = K\sqrt{P_{\text{gas}}} \tag{3}$$

where;

P_{gas} = partial pressure of the gas in contact with the metal

K = constant

The solidification process involves contraction or shrinkage since most of the materials are denser in the solid state than in the liquid state [15]. When one surface solidifies more slowly than the other, or if solidification begins at all surfaces of casting or pipes, the bulk of shrinkage occurs as cavities. Cavity shrinkage appears like a large void within a casting, while pipe shrinkage is in a form of a large conical shaped void at the surface of a casting.

Interdendritic shrinkage exists in aluminium alloys, which is small, normally isolated pores between the dendrite arms formed by the shrinkage that accompanies solidification. It is also known as the microshrinkage or shrinkage porosity. Fast cooling rates may reduce this problem, where the dendrites will be shorter, permitting liquid to flow through the dendritic network to the solidifying solid interface. Solidification time is determined using the Chvorinov's rule [15]:

$$t_s = B(V/A)^n \tag{4}$$

where;

V = volume of the casting and represents the amount of heat that must be removed before freezing occurs.

A = surface area of the casting in contact with the mould and represents the surface from which heat can be transferred away from the casting.

n = constant (usually ~2)

B = mould constant which depends on the properties and initial temperatures of both the metal and the mould.

Hence, applying modified stir casting route enables pre-heating of reinforcement material and bottom pouring casting, which are significant in obtaining a minimum level of porosity [7,19]. Apparently, the conventional stir casting route increases the probability of gas entrapment and water vapour entrance by adding the reinforcement particles into the matrix melt separately.

4.0 POROSITY EFFECTS ON MECHANICAL PROPERTIES

The mechanical behaviour affected by porosity formation in stir cast MMC is focused on tensile and fatigue properties [20]. Porosity tends to decrease the mechanical properties of MMC [2,11, 20-23]. Porosity formation which obviously depends on the matrix composition and microstructure, affects significantly the elastic modulus (E), yield strength (σ_Y), ultimate tensile strength (σ_{UTS}), and ductility (percentage elongation, %e) of the MMC [20]. Previous works are associated with the formation and growth of voids (porosity), with decreasing yield strength of composites [24], and reduction of the fatigue strength and total life time [25]. In an MMC analysis concerned with particle reinforced A356 MMC, the results indicated that porosity and other defects decreased the yield strength of A356/SiC/10p and A356/SiC/20p, where the average diameter of the particle was 10 μm [20]. More works on porosity has reported increase in total life time and fatigue strength, as the volume fraction and size of porosity increased [11]. Besides, a crack growth study of a cast A356 reinforced with 20% SiC_p concluded that short crack formation was associated preferably with porosity [25].

Figure 8 indicates that the decrease in instantaneous Poisson ratio for the MMC corresponds to the formation of porosity, as a result of higher volume fraction of reinforcement and larger reinforcement size. This is equivalent to the fact that increasing the volume fraction will increase the percentage of matrix to constraints and hence, unable to deform plastically [11]. Frequently, in many discontinuously reinforced

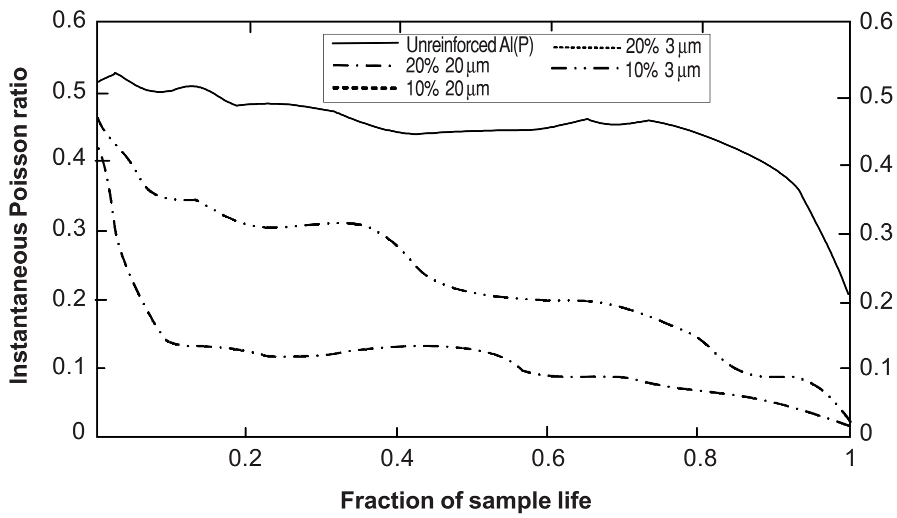


Figure 8 Instantaneous Poisson ratio as a function of specimen life for SiC reinforced Al composites [11]

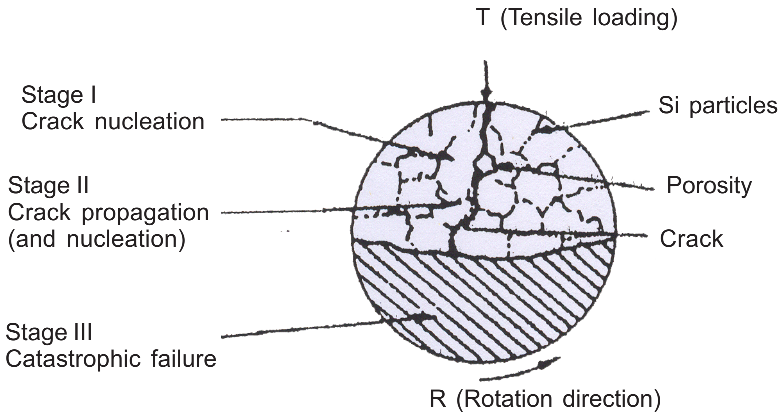


Figure 9 Fatigue failure of Al-7Si-0.3Mg alloy [21]

systems, specimen failure arises from the formation and growth of voids (Figure 9) at the reinforcement-matrix interface [21,22]. There are certain constraints on matrix plasticity which are unavoidable, but there are further reductions in ductility if microstructural feature such as voids is present [11]. Discontinuous MMC ductility relies on the strain at which damage nucleates, and the growth rate to cause failure [3]. It is predicted by considering the process of void coalescence which is expected to initiate failure. The cavities formation at high hydrostatic stress areas will work together by a ductile tearing mechanism, when a certain condition is established. Reinforcement particles (e.g. SiC_p) appeared to have a significant stress-raising effect on the formation of slip bands and cracks as there were micropores forming during solidification in the reinforced alloys, unlike the unreinforced. These micropores are preferred nucleation sites for fatigue cracks. In tensile test, porosity tends to develop the strain of a particular region in MMC, when stress is applied. Consequently, the ultimate tensile strength of a cast MMC will decrease (Figure 10), as well as the Young's modulus.

From a creep test data [27], the void content was higher in the necked region, compared to other deformed region. In the uniformly deformed region, test temperature rise and increasing load applied will increase the overall void contents. Crept specimen is observed to contain higher cavity levels at the necked region, compared to the specimen subjected to tensile testing. Shorter test (e.g. tensile test) and rapid rate of deformation did not exhibit the porosity content as much as the long term test, where more cavities tend to nucleate and grow under similar conditions of temperature, without immediately leading to failure. Figure 11 indicates the void content measured at the neck and deformed region in particulate reinforced Al, which produce linear correlations with the strain as the stress applied increased. Besides that, the particle size and volume fraction of reinforcement effect on porosity formation are compared in Figures 11 (a) and (b). In Al-SiC system, the large size (~20 μm) of particles influences

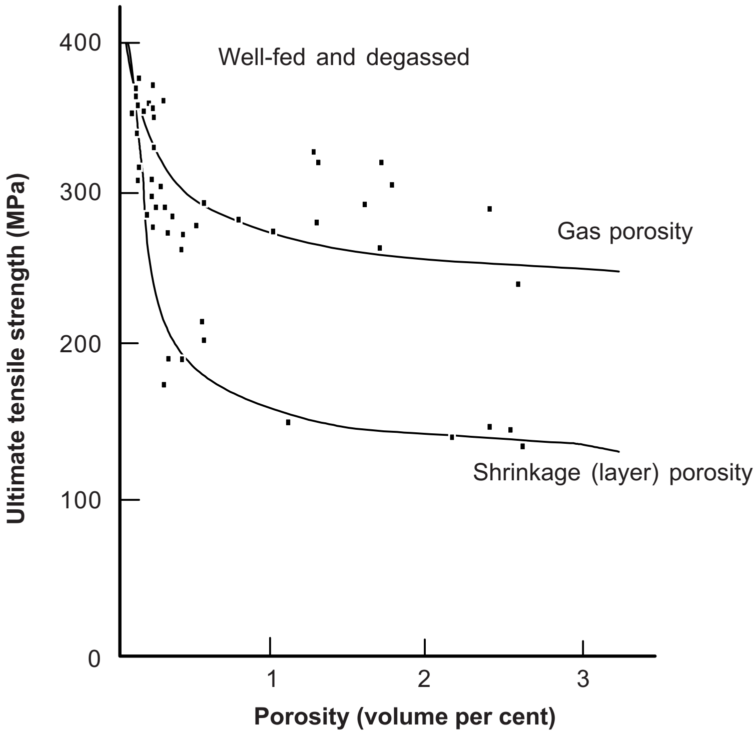


Figure 10 The reduction in UTS of an Al-11.5Mg alloy by dispersed porosity and by layer porosity [26]

fracture to occur. In fact, MMC containing finer reinforcements exhibits higher fatigue strength than coarser reinforcements, as shown in Figure 12 [27].

Furthermore, failure was suggested to occur when the associated neck cavitations reaches a critical value, where the critical value is dependant on the reinforcement volume fraction [11]. Another porosity effect is shown in Figure 13, where porosity formation increased the damping capacity, which is characterized using logarithmic decrement. Damping capacity is the ability of a material to absorb vibration (e.g. cyclic stress) by internal friction, and thus, converting the mechanical energy into heat [28]. According to the conversion mechanism at which point the porosity effect originates, the stress state may change from tension into shear at the boundaries of pores. Subsequently, the probability and density of dislocations around the pores will increase and thereby, the damping capacity [29].

Increasing ceramic particles content in MMC will drop the fracture toughness as the formation and merge of voids within the matrix tend to cause fracture in MMC. This is entirely expected and is consistent with the associated increase in constraint on matrix deformation and consequent reduction in ductility [2]. In fact, fatigue cracks initiate and propagate in regions, where the strain is most critical. In most cases, fatigue cracks initiate from surface discontinuities, which exist largely in materials, in highly

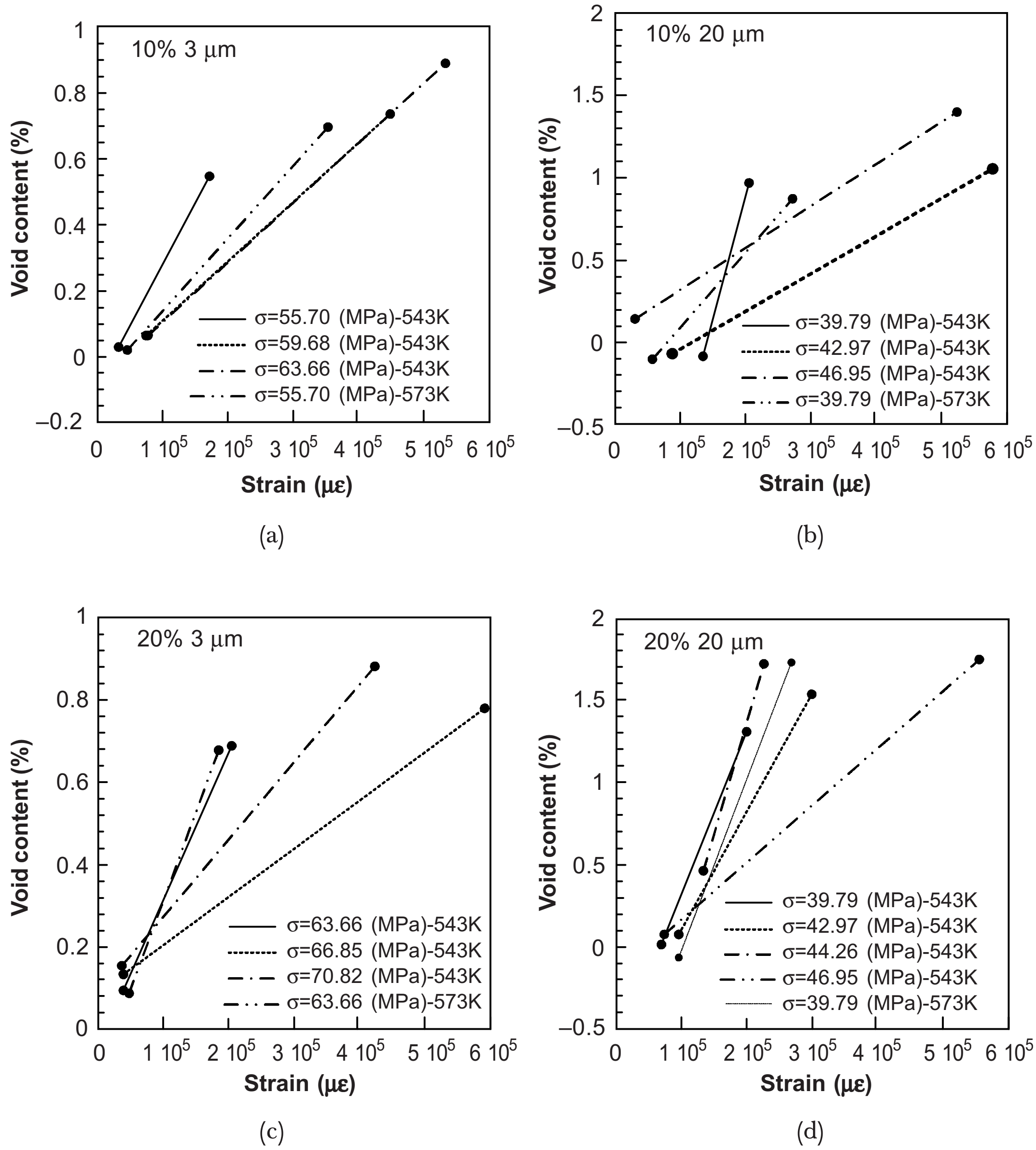


Figure 11 Void content of the specimen for SiC particulate reinforced Al composites as a function of applied stress [27]

stressed regions of the component. In this case, porosity happened to be the discontinuities, which lead to failure. Moreover, at elevated temperature (tensile stresses combined with high temperature), voids formation occurs at the particle-matrix interface and fatigue life of the particle reinforced material is reduced significantly [23].

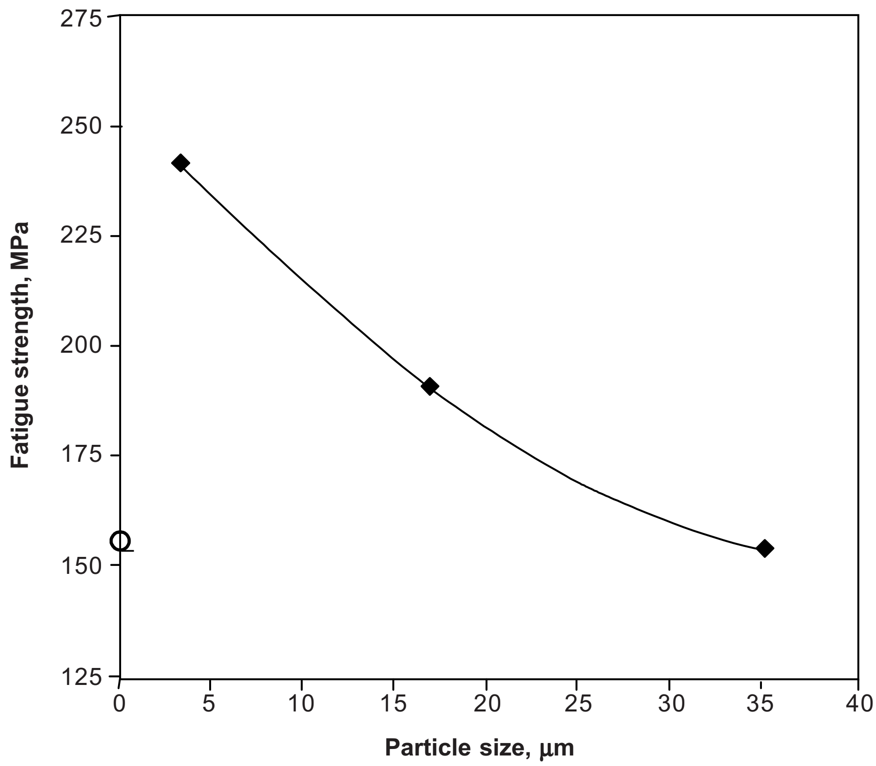


Figure 12 Effect of particle size on fatigue strength in 2124/SiC/20p (at 10 cycles, R=-1) [27]

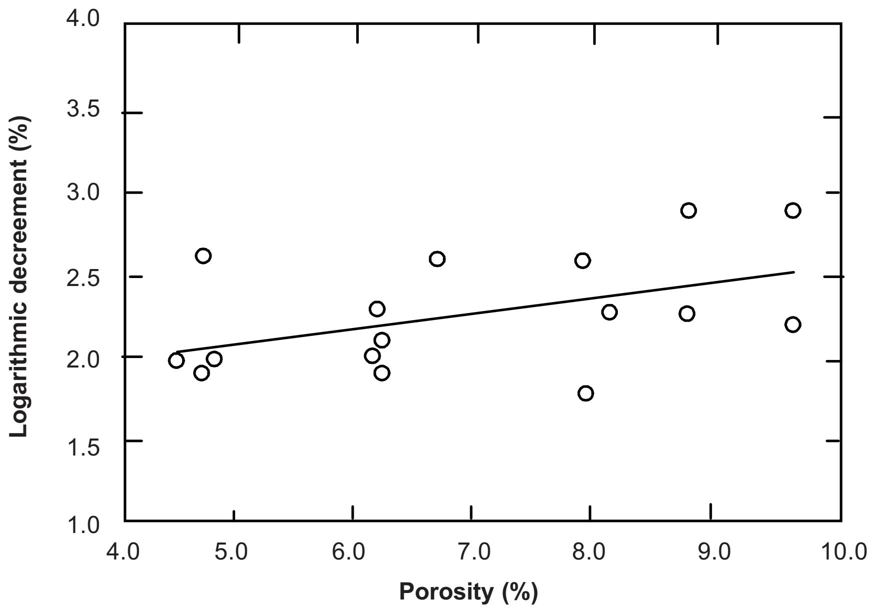


Figure 13 Relationship between damping capacity and porosity for 6061Al [28]

5.0 CONCLUSIONS

Porosity formation is largely caused by gas entrapment during vigorous stirring, air bubbles entering the slurry either independently or as an air envelope to the reinforcement particles, water vapour on the surface of the particles, hydrogen evaluation, shrinkage during solidification, and volume fraction of reinforcement material in MMC.

The presence of porosity, consequently, decreases most of the mechanical properties of cast MMCs. Failures initiated from the pores within the matrix material, particle fracture and reinforcement-matrix interface are due to voids coalescence, reduction of ductility, and reduced MMC cross section.

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