FRACTURE CHARACTERISTICS OF ALUMINUM CASTING ALLOYS

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ABSTRACT

Al-Si casting alloys are widely used for engineering applications especially for automobile industry. Data on mechanical properties of such alloys, however, are not yet enough and many studies are now required.

Fracture mechanisms in Al-Si system casting alloys are stated at first. Various morphologies of Si and α-dendrite in the alloys are examined in the relation to solidification microstructures and the presence of certain additives. Fracture behavior is analyzed in these alloys. Fracture toughness or impact toughness is measured and discussed. Effectiveness of modification of eutectic silicon morphology by Sr or Ca is specially stated. Furthermore, effect of impurity iron which is increased by recycling is also stated.

Fatigue properties of Al-Si system alloys are presented. If there is no debris by coarse silicon on the specimen surface, K-N curve shows better fatigue strength rather than wrought 6061-T6 alloy. Increase of Si content leads to the increase of ΔK_{th} value, but the slope at the Paris region becomes large. Moreover impact fatigue test is conducted. Fatigue properties are generally degraded in this test.

To assure the safety at impact collision during transportation of vehicles, exact dynamic stress-strain relationship is required for the simulation analysis. Dynamic tensile test using closed loop type high speed testing machine, therefore, is carried out up to the velocity of 12m/s.

Keyword: *Al-Si casting alloy, fracture toughness, fatigue, impact tensile test*

1. INTRODUCTION

Aluminum casting alloys are now increasingly used in various fields. They are increasing in their use mainly in the field of automobile industry because of their excellent specific strength. Recently, automobiles are required to lighten the weight for the saving of the fuel and assure the safety for the various accidents. Furthermore, the usage of recycled aluminum is increasing. It becomes, therefore, important to investigate the mechanical properties(strength, fracture toughness and fatigue characteristics) of the aluminum casting alloys from various points of view. In as cast materials, there are many heterogeneous casting defects, i.e. materials generally include microsegregation, macrosegregation, gas pores, shrinkage pores, coarse crystalline structures or nonmetallic inclusions during solidification.

In this paper, the effect of the microstructure in the aluminum casting alloys on tensile properties, fracture toughness, fatigue characteristics, impact fatigue characteristics and dynamic tensile properties are reviewed mainly based on the author's study.

2. SOLIDIFICATION STRUCTURES AND FRACTURE TOUGHNESS

2.1 Effect of second phase

Generally, aluminum casting alloys, like other casting alloys will form dendrite during solidification. A schematic diagram illustrating the dendrite growth during solidification is presented in **Fig.1**[1]. In metals which solidify dendritically, the inclusion appears in the interdendritic spaces. The pore also nucleates in the interdendritic spaces. The inclusion and the pore formed during solidification often become crack origins in the casting alloys.

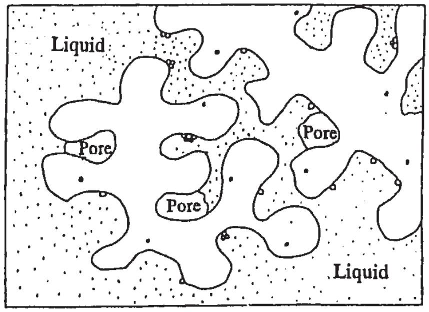

Fig.1 Schematic illustration of microstructure during solidification.

In aluminum casting alloys, fracture occurs in ductile manner by void initiation at eutectic silicon particles and inclusions[2]. In the case of dimple type fracture, the coarse particles (Fe, Mg, Cu and Si type nonmetallic inclusions) in a range of 0.1-10μm become crack initiation sites. The sequence of fracture events is as follows; void nucleation at these coarse particles, void growth and coalescence of individual voids. If intermediate particles (Cr, Mn and Zr type inclusions) in a range of 0.05-0.5μm and fine precipitation particles in a range of 0.01-0.5μm exist in the matrix, voids are connected through micro-voids[3]. In this case, ductility is decreased rather than voids by only coarse particles. If coarse particles do not exist, dimples formed by only fine precipitation particles show higher ductility[3].

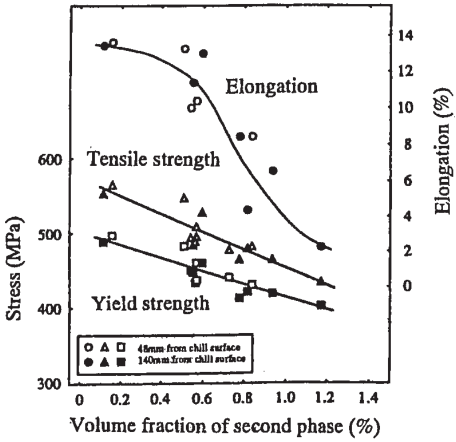

Fig.2 Relationship between mechanical properties and second phase in 7075 aluminum alloy.

Figure 2 illustrates the effect of the amount of second phase (coarse particles in a range of 0.1-10μm) on the tensile properties of 7075 aluminum alloy solidified directionally[4]. Strength and elongation increase with decreasing the volume fraction of the second phase, especially in elongation. However, mechanical properties of the commercial Al-Si casting alloys are known to be largely dependent on the eutectic silicon characteristics (i.e. size and morphology) as well as the eutectic silicons spacing. In this case, microvoids coalescence occurs by a process involving fractures at silicon particle and silicon-matrix interface.

2.2 Effect of dendrite coarseness

Mechanical properties of the casting alloys are known to be largely dependent on the dendrite arm spacing and cell size. As dendrite cell size decreases, tensile strength and elongation increase. **Fig.3** shows an interesting result by regression analysis on the effect of various factors in equiaxed and columnar crystal grains(grain size: λ_0, primary dendrite arm spacing: λ_1) on ultimate tensile strength and elongation in Al-4.5%Cu casting alloy[5]. This figure suggests that the solubility of element(C_M) exerts the largest effect on the tensile strength, and volume fraction of θ phase, f_θ exerts the largest effect on the elongation. If the solubility of the element is constant, the relationship between the tensile strength, σ_B and the secondary arm spacing, λ_2 is shown as **Fig.4**[5]. σ_B and λ_2 are described as Hall-Petch relationship ($\sigma_B = \sigma_0 + k\lambda_2^{-1/2}$), where k value varies with f_θ. It should be noticed that k becomes zero when f_θ is zero.

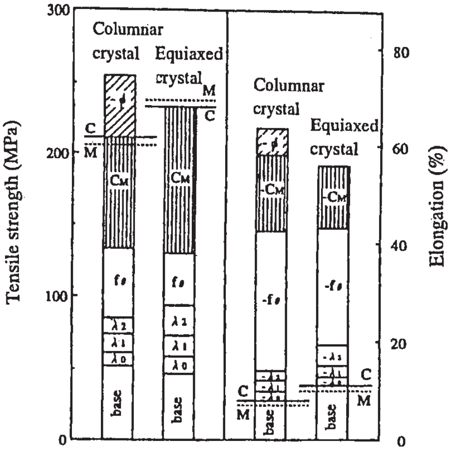

Fig.3 Relationship between mechanical properties and dendrite size in Al-4.5%Cu casting alloy.

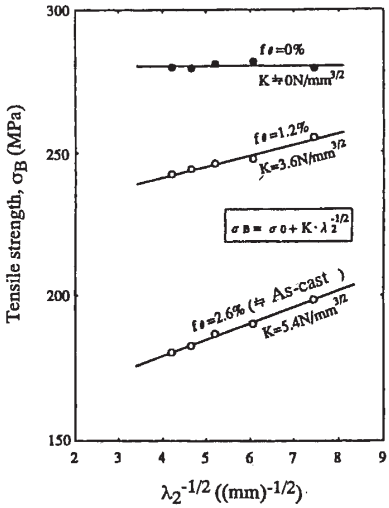

Fig.4 Relationship between tensile strength and secondary dendrite arm spacing in Al-4.5%Cu casting alloy.

Toughness of Al-0.5%Fe casting alloy is dependent on dendrite cell size rather than grain size, dendrite cell size becomes finer, resulting in the higher toughness[6]. However, according to the recent proposal[7,8], mechanical properties are dominated directly by eutectic phase distribution. The structural integrity parameter, φ, therefore, has been presented **(Fig.5)**. The relationship between the dynamic fracture toughness and the dendrite arm spacing(λ_2) is shown in **Fig.6(a)**. In **Fig.6(b)**, the fracture toughness data is related to the structural integrity parameter φ (=MFP/ λ_2). Better correlation between the dynamic fracture toughness as well as the other mechanical properties and the parameter has been noted[9]. Therefore the proposed structural integrity parameter is a promising factor having an influential role in controlling the mechanical properties and the deformation behavior of hypoeutectic Al-Si alloys at certain stages in the fracture process.

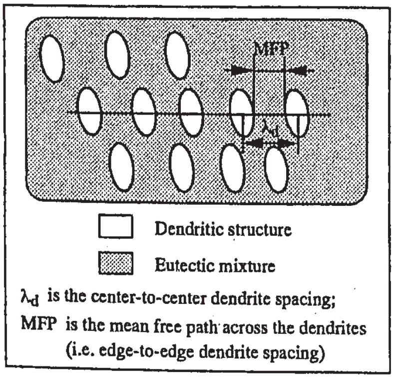

Fig. 5 Schematic illustration of the microstructural parameters considered in hypoeutectic Al-Si casting alloy.

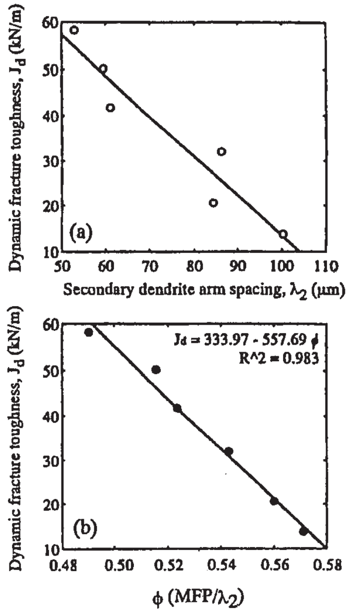

Fig.6 Relationship between fracture toughness and secondary dendrite arm spacing and ϕ factor in high purity Al-8%Si casting alloy.

2.3 Effect of gas content

Figure 7 shows the relationship among gas(almost hydrogen) content, primary dendrite arm spacing and Charpy absorbed energy of Al-3%Mg casting alloy as a function of directional solidification rate[10]. In the solidification rate range between 5.56×10^{-2} and $2.22\times^{-1}$m/s, gas content increases with increasing solidification rate. On the other hand, primary dendrite arm spacing decreases with increasing solidification rate. In this range, the absorbed energy increases with solidification rate; however, in as cast state where the dendrite becomes most fine, the absorbed energy shows the lowest. Probably this fact may be caused by the appearance of shrinkage cavity in the as cast sample.

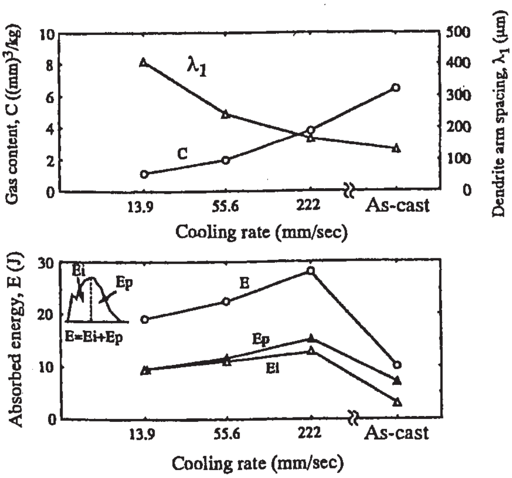

Fig.7 Relationship among gas content, primary dendrite arm spacing, absorbed energy and cooling rate in Al-3%Mg casting alloy.

2.4 Effect of impurity Iron

Iron is the most commonly acquired impurity element in aluminum casting alloys affecting the fracture toughness due to the formation of needle-like Fe-Al based intermetallic compounds. The amount of needle like Fe-Al based intermetallic compounds increase with Fe content in aluminum casting alloys like Al-Si system casting alloys by recycling, and they degrade the mechanical properties and fracture toughness. The effect of iron on the dynamic fracture toughness, J_d and tearing modulus, T_{mat} of Al-Si-Cu system aluminum casting alloy are shown in **Fig.8**. It is found from **Fig.8** that J_d'and T_{mat} decrease with the increasing Fe content. However, it has been clarified that J_d and T_{mat} are improved when Ca is added to AC2B-T6[11]. In order to achieve good toughness, morphologies of eutectic silicon and needle-like Fe-Al or Fe-Al-Si type intermetallic compounds should be modified and heat treated [11,12].

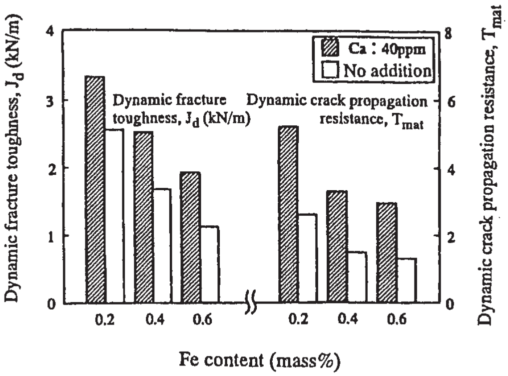

Fig.8 T_{mat} and dynamic fracture toughness versus Fe content in AC2B-T6 casting alloy with and without Ca addition.

2.5 Effect of modification

The remarkable microstructural changes in hypereutectic Al-Si alloys can be produced by treating the melt with additives that introduce a small amount of phosphorus. In order to improve the toughness, Si particles must be refined and spheroidized. For many years, sodium (Na) has been the prevailing modifying agent for hypoeutectic Al-Si casting alloys. However, the problems associated with the use of Na as a modifier attracted many investigators to research for alternative element(s) for modifying Al-Si alloys. Recently, strontium (Sr) or stibium (Sb) has been accepted as a modifier, respectively. Typical microstructures of AC4CH (Al-Si-Mg

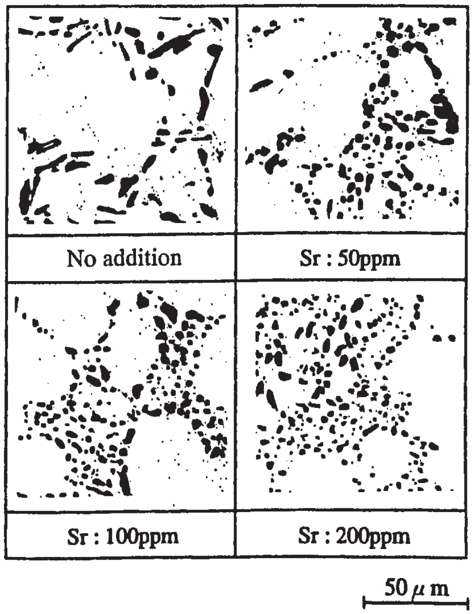

Fig.9 Microstructures of AC4CH-T6 casting alloy with various Sr additions.

3.2 Comparison with wrought aluminum alloy

The relationship between fatigue crack propagation rate, da/dN and nominal cyclic stress intensity factor range, ΔK in the wrought 6061-T6 alloy, AC4C-T6 casting alloy and AC8A(Al-Si-Ni-Mg system)-T6 casting alloy is shown in **Fig.15** [18]. Threshold values of casting alloys are higher than the wrought alloy. Hence, crack growth rates are slowest for the wrought 6061-T6 alloy at the Paris region. S-N curves obtained from fatigue test in the same materials are shown in **Fig.16**[18]. The wrought alloy shows better fatigue strength than the casting alloys. However **Fig.17** shows K-N curves corrected by $K=\sigma(\pi d)^{1/2}$ parameter, where d is a size of debris caused by coarse silicon near the surface. If there is no debris by coarse silicon on the specimen surface, K-N curves of casting alloys show better fatigue strength rather than the wrought 6061-T6 alloy. Increase of Si content leads to the increase of ΔK_{th} value, but the slope at the Paris region becomes large.

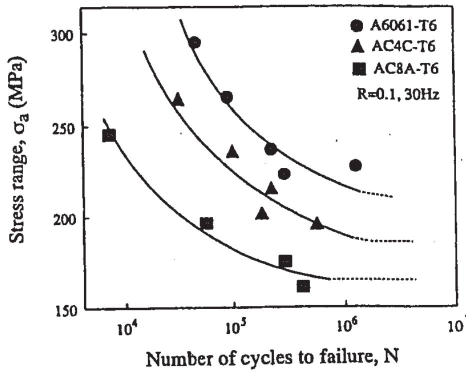

Fig.16 S-N curves obtained from fatigue test in Al-Si system casting alloys and A6061-T6.

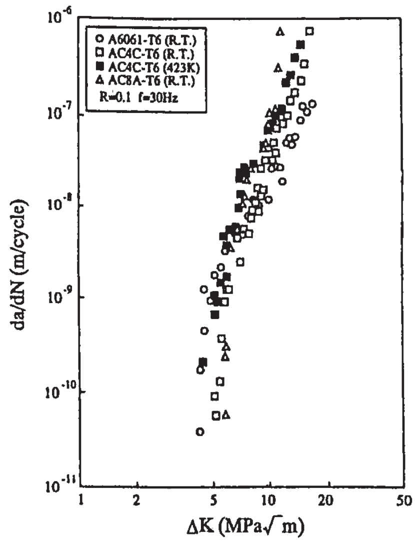

Fig.15 Relationship between da/dN and ΔK in Al-Si system casting alloys and A6061-T6.

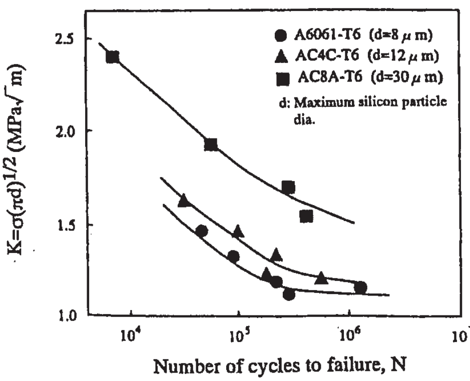

Fig.17 Relationship between $K=\sigma(\pi d)^{1/2}$ and number of cycles to failure in Al-Si system castings alloy and A6061-T6.

the porosity on the static fracture toughness, J_{IC} of various aluminum casting alloys[15]. As can be seen, fracture toughness decreases with increasing porosity in all materials. As porosity increases, it leads to the decrease of J_{IC}.

Figure 12 illustrates the effect of the maximum pore size at the crack tip on the static fracture toughness, J_{IC} of AC4C-T6 and AC4CH-T6 casting alloys[15]. A good correlation between log of the maximum pore area at the crack tip and J_{IC} are recognized.

3. FATIGUE CHARACTERISTICS

3.1 Effect of Si content

Al-Si system casting alloys are widely used for the components of automobiles or aircrafts over a wide range of Si content. They are often used under cyclic loading conditions, that is, fatigue conditions. Fatigue characteristics of aluminum casting alloys as a function of Si content have been investigated[16,17]. The relationship between fatigue crack propagation rate, da/dN and stress intensity factor range, ΔK in various Al-Si casting alloys are shown in **Fig.13**. Crack propagation rate is the fastest in Al-20%Si alloy in the higher ΔK range. **Fig.14** shows the relationship between effective threshold stress intensity factor range, $\Delta K_{eff.th}$ and Si content. $\Delta K_{eff.th}$ increases with increasing of Si content in as-cast and solution treated alloys[16,17].

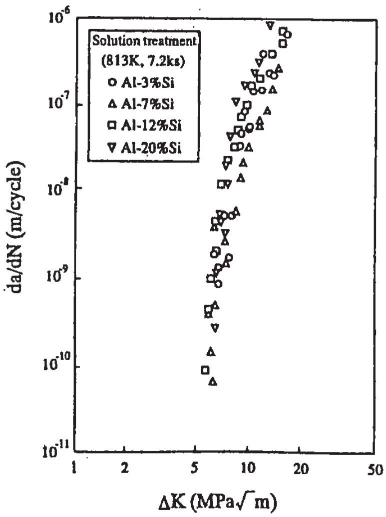

Fig.13 Relationship between da/dN and ΔK in Al-Si casting alloys.

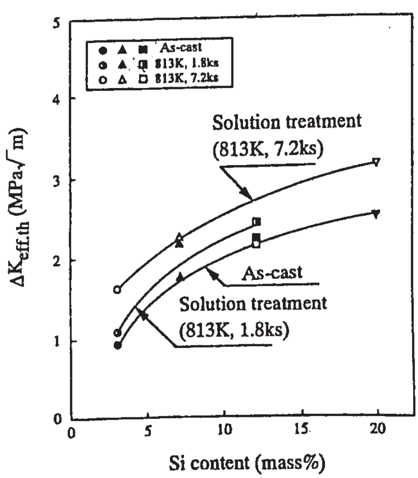

Fig.14 Relationship between effective threshold cycle stress intensity factor range and Si content in Al-Si casting alloys.

system)-T6 casting alloys containing 0 to 200ppm Sr are shown in **Fig.9**[13,14]. **Fig.10** represents the variation of the static fracture toughness, J_C and dynamic fracture toughness, J_d with Sr content[15]. J_C and J_d of AC4CH-T6 are strongly improved by adding Sr. These improvements in J_C and J_d can be attributed to the relative fineness and scale down of eutectic Si particles by modification.

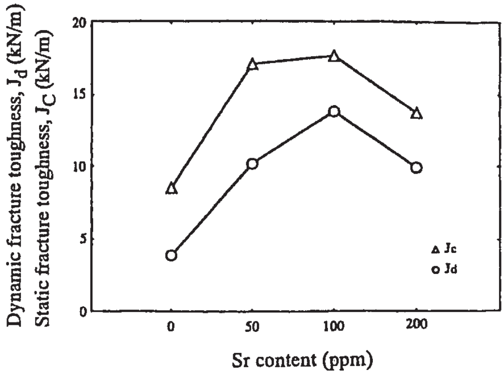

Fig.10 Effect of Sr addition on static and dynamic fracture toughness in AC4CH-T6 casting alloy.

The dynamic fracture toughness, J_d and tearing modulus, T_{mat} of AC2B-T6 aluminum casting alloy containing 40ppm Ca have been already shown in **Fig.8**. Calcium (Ca) also has been accepted as a modifier. The small addition of Ca, as stated in the previous section, has been found to be effective to improve the toughness of Al-Si system casting alloys with relatively greater content of Fe because Ca modifies also Al-Si-Fe based intermetallic compounds.

2.6 Effect of casting defects

Casting defects(various pores or cavities) become crack origins. **Fig.11** illustrates the effect of

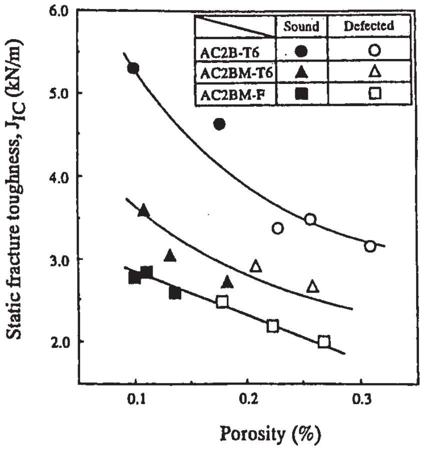

Fig.11 Relationship between fracture toughness and porosity in AC2B-T6, AC2BM-T6 and AC2BM-F alloys. M shows containing of Mg.

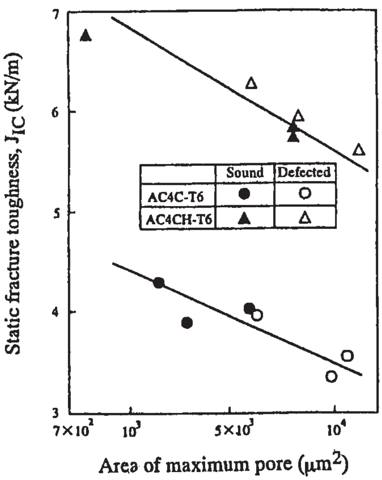

Fig.12 Relationship between J_{IC} and maximum pore area in AC4CH-T6 casting alloy.

3.3 Effects of impurity Iron and modification by Ca in impact fatigue test

Many components are often operated under repeated impact loading conditions. However, such data have been reported little. S-N curves obtained from impact fatigue test in AC2B-T6 casting alloy containing 0.2 to 0.8 mass% Fe content are shown in **Fig.18**[11]. Relationship between maximum stress and the number of cycles to failure shows linear lines with log-log scale in the figure. It can be seen that in each Fe content, S-N curves cross each other at the number of about 10^5 cycles irrespective of Ca addition. This means that in low cycle life region, fatigue strength of the alloys decreases with increasing Fe content. However, this tend is opposite in high cycle life region, namely fatigue strength increases with increasing Fe content. The decrease of fatigue strength with increasing Fe content in the low cycle region could be explained by the fact that dynamic fracture toughness decreased independent of Ca addition amount in the previous report[12]. It seems Fe intermetallic compounds play a different role in the high cycle region. They will affect the fatigue crack propagation behavior. Crack deflection is obvious in the high cycle region. And the impact fatigue strength of Ca added specimens is higher than that of Ca unadded ones.

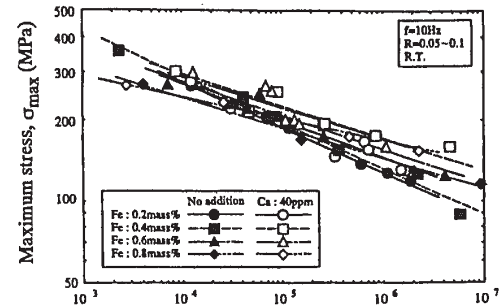

Fig.18 S-N curves obtained from impact fatigue tests of AC2B-T6 casting alloys with and without Ca addition.

The relationship between fatigue crack propagation rate, da/dN and nominal cycle stress intensity factor range, ΔK in AC2B-T6 casting alloy containing 0.2 mass% Fe content is shown in **Fig.19**. The retardation of da/dN is pronounced when Ca is added in this alloy.

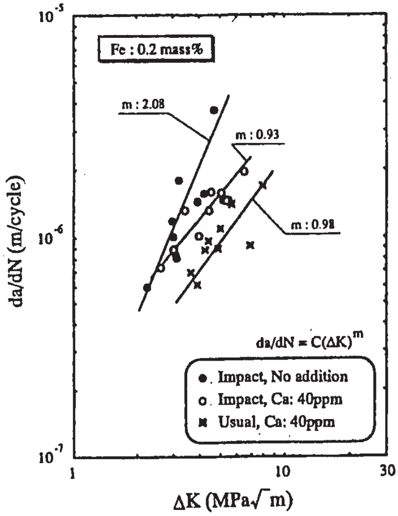

Fig.19 da/dN - ΔK curves obtained from impact and usual fatigue tests of AC2B-T6 casting alloys.

Comparison between impact and usual fatigue tests in AC2B-T6 alloy containing 0.2 mass% Fe content is shown in **Fig.20**[11]. It is generally said if the abscissa is expressed with cumulative time N • T_e, where N is the number of cycles to failure and T_e is duration time of each loading cycle, a linear stress-N • T_e relation may be obtained in the impact fatigue tests. However, this relation is not established well between the impact and usual fatigue tests. However, it is clearly shown in the figure that the impact fatigue strength of the alloy is inferior to the usual fatigue strength.

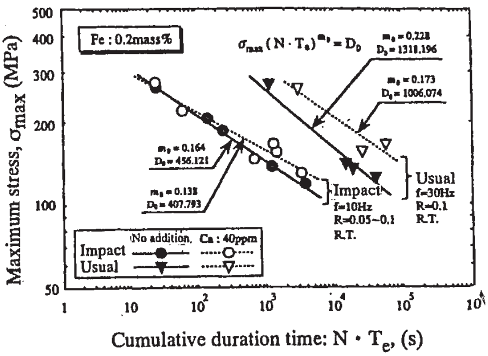

Fig.20 S - N • T_e curves obtained from impact and usual fatigue tests of AC2B-T6 casting alloys.

4. DYNAMIC TENSILE PROPERTIES

Dynamic tensile test under various loading velocities from 0.01m/s to 12m/s have been carried out using closed loop type high speed testing machine(capacity: 5ton). Specially designed specimen with two stepped gage length is used to detect the load from the attached strain gage at the elastic deformation portion[19]. Load signal from the testing machine is imposed inertial loading and it is impossible to be analyzed.

Typical load-deflection curve of AC4CH-T6(Al-7.1Si-0.35Mg) alloy is shown in **Fig.21**. At that time, the changes of yield stress, tensile stress and total elongation with nominal strain rate are shown in **Fig.22**.

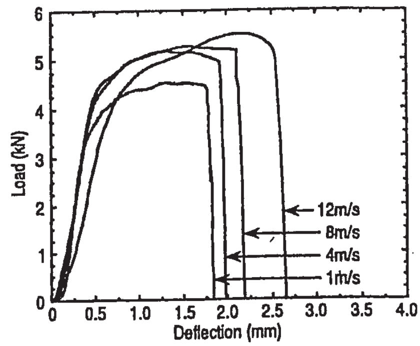

Fig.21 Typical load-deflection curves recorded in the impact tensile test.

Although it has been reported that aluminum alloys do not show remarkable change in strength or elongation in this strain rate range($\sim 10^3$/s), more detailed studies should be made hereafter.

5. Conclusion

Aluminum casting alloys are increasing in their use for their light weight benefit mainly in the automobile industry. However, their physical and mechanical properties have not been studied enough. Especially fracture characteristics must be studied more for assurance of safety for application to vehicles or aircraft. This article will give a suggestion on the direction of such studies.

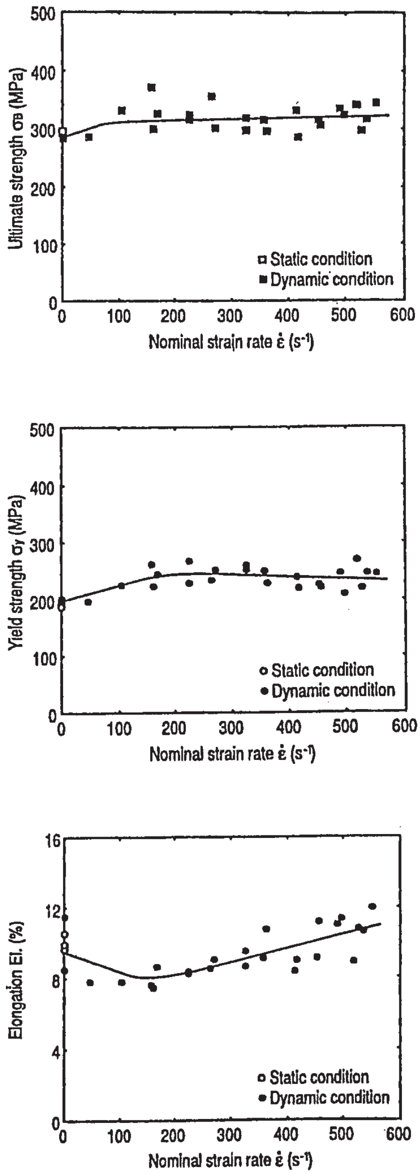

Fig.22 Relationship between tensile properties and nominal strain rate in AC4CH-T6 casting alloy.

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