FRACTURE RELATED MECHANICAL PROPERTIES OF AIRCRAFT CAST ALUMINUM ALLOY A357

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ABSTRACT

The fracture related mechanical properties of the A357 cast aluminum alloy were investigated. The mechanical properties investigated were Charpy impact resistance, tensile strain energy density (tensile toughness), tensile elongation to fracture and plain strain fracture toughness. The correlation of the above mechanical properties had been justified for both, 25 different artificial aging heat treatment conditions and for 5 minor variations in chemical composition of the widely used in the aeronautics A357 cast aluminum alloy. Different empirical correlations are proposed to establish useful relationships between (a) impact resistance and strain energy density and (b) strain energy density and fracture toughness, respectively. The established correlations, which are well supported by the performed experiments, can be used to estimate the tensile ductility and toughness of the A357 cast aluminum alloy from the Charpy impact test, or to estimate its plain strain fracture toughness from the tensile toughness values. Performed fractographic analyses were supporting the physically arbitrary correlation between tensile strain energy density and impact resistance.

Introduction

Precision casting is currently attracting considerable attention as a reliable manufacturing process for producing aeronautical and automotive aluminum components of complex shape geometries cost efficiently. Inferior mechanical properties, specifically in terms of ductility and toughness, and increased scatter compared to the respective wrought aluminum alloys, represent serious drawbacks for their increased exploitation in aeronautical applications. The tighter controls currently applied during the casting process, as well as the advancements on the casting processes and the better understanding of the physical metallurgy background of the age-hardened aluminum alloys led to an improvement of the material quality and, hence, to an appreciable increase of the competitiveness of aluminum casting products. The most widely used alloy for the above applications is the precision-hardened Al-Si-Mg A357 cast alloy. Alloy A357 with minor modifications in chemical composition has been extensively investigated in recent research projects, e.g. [1-3].

The characterization of the quality of a cast alloy involves non-destructive inspection, quantitative metallography and mechanical testing, e.g. [4]. Hardness, tensile and impact testing are in principal used to characterize the quality of a cast aluminum alloy in terms of mechanical performance. The demands for increased damage tolerance abilities of cast aluminum alloys have made fracture and tensile toughness important properties. The material property fracture toughness is quite underestimated for the case of cast aluminum alloys. The fracture toughness test, due to its complexity, is usually not performed to cast aluminum alloys and more ‘fast’ tests, e.g. hardness and tension test are performed to evaluate the mechanical performance of these alloys. Notice that in aircraft and automotive industry, certain minimum values in tensile strength, ductility and fracture toughness are prerequisite for considering a material as a candidate for structural applications. e.g.[1]. Empirical and analytical correlations had been proposed in the literature to calculate or estimate the fracture toughness of several materials from easy to perform tests, such as the impact or the tension test.

In the early 70’s the empirical equation (1) was proposed by Barson and Rolfe [5], for both, low-alloyed and austenitic steels to calculate the alloy’s plane strain fracture toughness K_{Ic} for known Charpy V-notch impact energy W_{CVN} and yield strength values R_p.

$$\left(\frac{K_{Ic}}{R_p}\right)^2 = m \cdot \left(\frac{W_{CVN}}{R_p}\right)^2 + n \quad (1)$$

The m and n coefficients are both, empirical and material dependent constants. However, the correlation of the material's fracture toughness and impact energy has not been reported on the open literature for aluminum alloys.

In the present work, the material property impact resistance R_{CVN} has been empirically related to the material's strain energy density W. To this end, the strain energy density W has been involved in eqn.(1) instead of the plane strain fracture toughness K_{Ic}, for the case of cast aluminum alloys. According to Yeong et al. [6], strain energy density W is proportional to K_{Ic}^2, thus providing a background for this assessment. Different empirical correlations are proposed to establish useful relationship between R_{CVN} and W. Performed fractographic analyses by using a scanning electron microscope are supporting the physically arbitrary correlation of tensile strain energy density and impact resistance. In addition, the strain energy density of the material had been empirically correlated with the plain strain fracture toughness for A357 cast aluminum alloys with variations in chemical composition.

Experimental

The material used for the investigations was A357 aluminum alloy cast ingot and A357 alloy with minor variations in chemical composition. The A357 ingots were supplied by Pechiney, France and were cast with continuous casting process and delivered in form of rods. The use of ingots instead of cast material has been preferred to keep imperfections such as porosity and other inclusions minimal and, hence, to reduce deviations in mechanical properties. The chemical composition of the delivered ingot material was Al-7,0Si-0,55Mg-0,10Ti-0,12Fe-<0,10Mn. For the experimental investigation, specimens for microstructure characterization, hardness measurements, tensile tests and Charpy impact tests were cut from the middle section of the ingots to obtain the same solidification conditions. The cast alloys with variations in chemical composition were produced by Ciral, by exploiting the patented casting method SOPHIA in the framework of BRITE/EURAM project ADVACAST [1]. The test program included the addition of 1%Cu to the reference A357 alloy. Further modifications by using, in addition to copper, a further alloying element (namely Ag or Sm or Sr) had also been made. Tensile and fracture toughness specimens were cut from a 30 mm casted plate.

The cast ingot specimens were solution heat treated for 22 hrs at 540^{o}C and quenched in water <10^{o}C, as proposed in [1]. Artificial aging of the specimens was made at the temperatures 155, 175 and 205^{o}C which cover the range of temperatures involved for artificial aging of commercial A357 cast alloys, [7,8]. The heat treatments of the investigated A357 alloy modifications can be found in the respective report of the project [1].

The cast aluminum alloys were experimentally evaluated by performing hardness, tensile, impact and fracture toughness measurement tests as well as fractographic analyses for both, tensile and impact specimens. Details about the tensile experiments, the hardness measurements and the metallographic analyses of as cast as well as heat-treated alloys can be found in [9]. The fracture toughness specimen configuration was a C(T) specimen of 40 x 48 mm and 20 mm thickness. The specimens were cut according to the ASTM E399 standard. Three tests had been performed to get an average value. Details about the testing procedure can be found in [1].

For the impact tests, full size Charpy V notch 10 x 10 x 55 mm impact specimens according to ASTM E23 were used. The tests were carried out on an Instron Wolpert instrumented impact-testing machine with maximum dynamic force of 40 kN, controlled by a computer. For each artificial aging condition at least six impact specimens were tested to get an average data point. In total 159 impact tests were performed. To characterize the predominant fracture mechanisms of the investigated tensile and impact test specimens, fracture surface analyses were made. For the fracture surface analyses a Phillips FEG/SEM XL40 scanning electron microscope, with an operating voltage of 20 kV equipped with an EDX system, was used.

Results

The results from tensile tests, hardness measurements as well as metallographic analyses of as cast and heat-treated alloys had been presented and discussed in detail in [9]. Briefly, the performed hardness measurements and metallographic analyses have shown that for artificial aging at 205^{o}C the peak hardness condition of the alloy was reached at about 8 hours. At aging times higher than 16 hours, an overaging of the alloy was observed. At 175^{o}C, for the investigated aging time range up to 48 hours, no indications of overaging were observed. Peak hardness at 175^{o}C was observed at aging times lying between 20 and 48 hours. At 155^{o}C hardness did not reach a peak value within the investigated aging time range of 48 hours. As the hardness of the material increases with the increasing artificial aging time, it is expected that the tensile ductility will decrease [7,8]. Typical engineering tensile stress-strain curves for three different artificial aging times can be seen in Figure 1.

Typical impact force – displacement curves of the investigated A357 alloy can be seen in Figure 2. The points of impact yielding, maximum force, stable and unstable crack propagation can be seen in the respective Figure as different points. The Charpy V notch impact energy values W_{CVN} had been calculated as the integral below the impact force – displacement curves. In order to relate impact energy to the material's toughness, impact resistance R_{CVN} values were calculated. The term R_{CVN} was defined as:

$$R_{CVN} = W_{CVN}/F_0, \tag{2}$$

with F_0 being the reduced cross-section area of the impact specimen. The dependence of the impact resistance R_{CVN} on the aging time for the aging temperatures investigated can be seen in Figure 3a. The aging times of the specimens for the impact tests were selected such as to avoid overaging, and thus obtaining the same impact fracture mechanism. The impact resistance decreases with increasing time from the initial value of 155 kJ/m^2 for the material before aging and tends to a value about 75 kJ/m^2 after artificial aging for peak tensile strength values. The observed dependency of the impact resistance on the aging time correlates well to the decrease of tensile strain energy density W with increasing aging time (Figure 3b). It should be noticed that, as tensile strain energy density and impact resistance refer to mechanical load application rates that differ by more than five orders of magnitude, their direct correlation is not a straightforward issue.

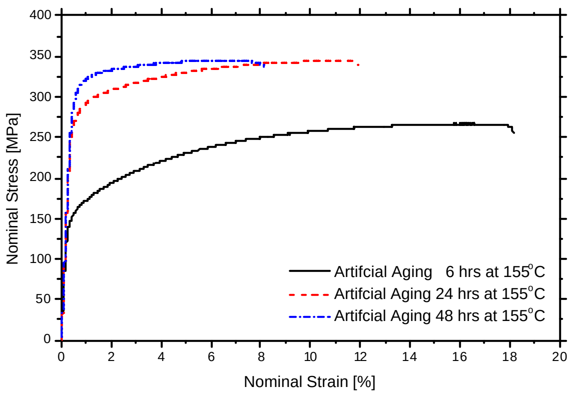
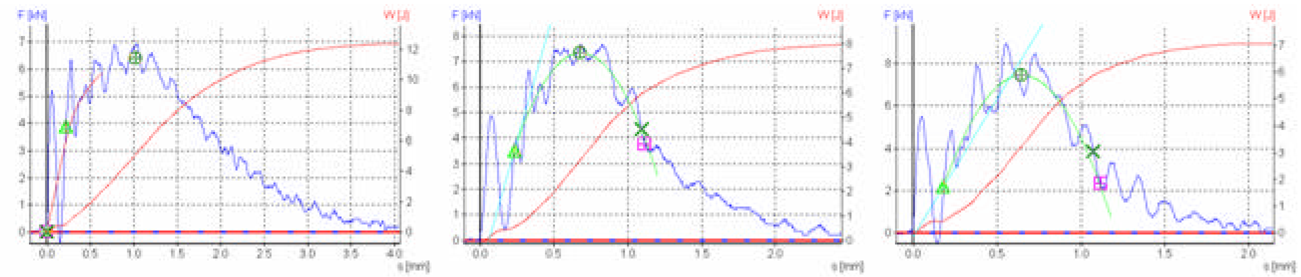


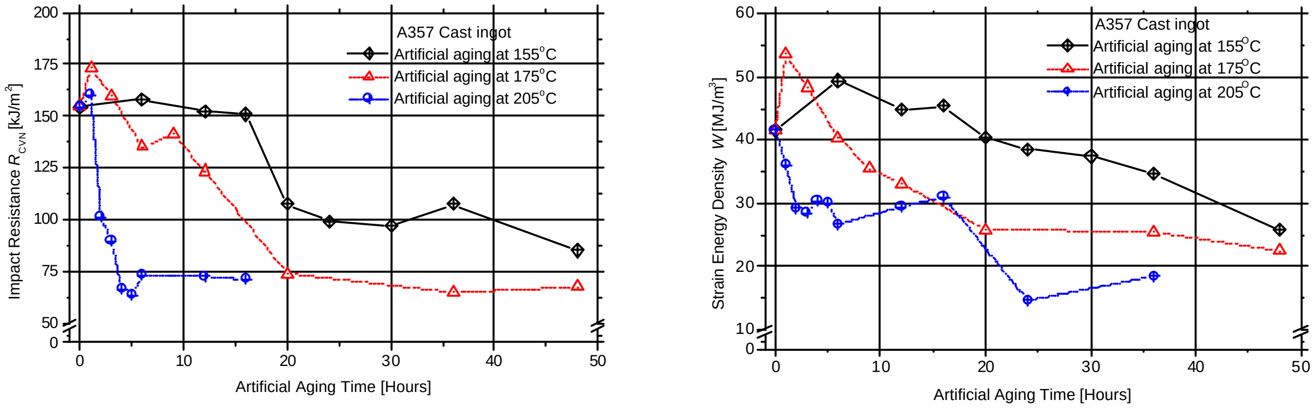
Figure 1. Typical engineering stress – strain tensile flow curves of the A357 cast aluminum alloy for different artificial aging heat treatment times.



(a) (b) (c)

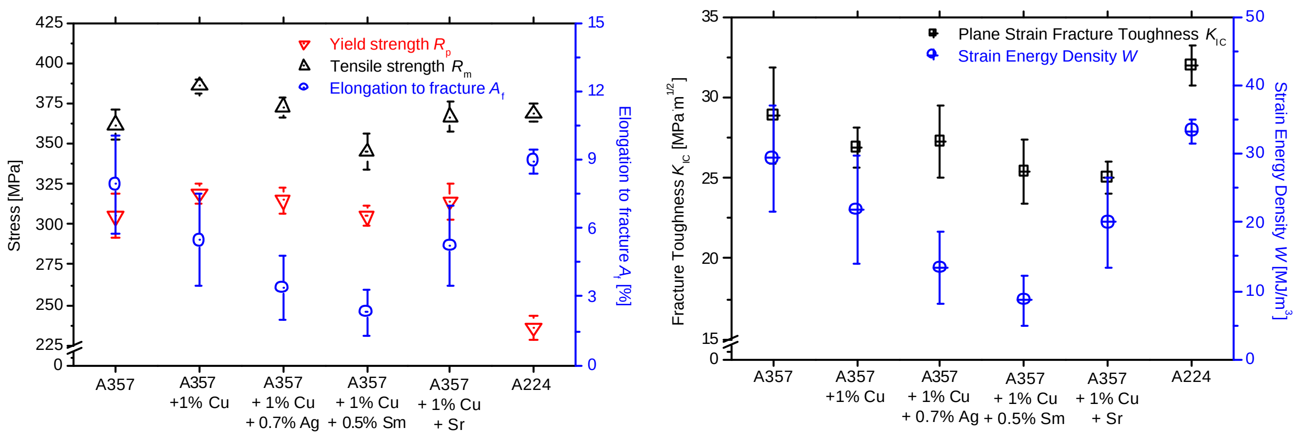
Figure 2. Typical impact force – displacement curves of the investigated A357 cast aluminum alloy for (a) 6 hrs, (b) 24 hrs and (c) 48 hrs artificial aging time at 155°C.

The mechanical properties of the cast aluminum alloys with variations in chemical composition can be seen in Figure 4. The yield strength R_p, the tensile strength R_m, elongation to fracture A_f can be seen in Figure 4a, as well as both, strain energy density W and fracture toughness K_{Ic} values in Figure 4b. Briefly, the 'reference' alloy A357 represents a well-balanced alloy of medium strength properties and high ductility – fracture toughness values. The addition of 1%Cu increased the strength properties, and decreased both, ductility and fracture toughness values. The further addition of Ag or Sm on the A357+1%Cu had almost the same effect: the strength level and the fracture toughness was practically unchanged, but an essential decrease in ductility was observed. The Sr addition to the copper modified alloy didn't have a significant effect on the tensile mechanical properties, but a small decrease on the fracture toughness value. For comparison, in the framework of [1], an Al-Cu A224 cast aluminum alloy had been also produced. The mechanical properties of A224 alloy had been also used in the present work for comparison purposes. A224 alloy is a high ductility – fracture toughness alloy, with a low yield strength $R_{p0,2\%}$ value. More details about the microstructural features of the alloys and about the tensile and fracture toughness test results can be found in [1,10,11].



(a) (b)

Figure 3. Effect of different artificial aging heat treatment conditions on (a) impact resistance R_{CVN} and (b) strain energy density W of the investigated A357 cast aluminum alloy.



(a) (b)

Figure 4. Effect of variation in chemical composition on the (a) yield strength R_p, tensile strength R_m, elongation to fracture A_f, and (b) plain strain fracture toughness K_{Ic} and strain energy density W of the investigated cast aluminum alloys.

Analysis of the Results

It is reported in the literature that the elongation to fracture A_f is analogous to the material's toughness for the case of ductile materials [8,12]. In this work, a direct correlation of these two – fracture related – properties is attempted for the investigated artificial aging heat treatment conditions of the A357 cast aluminum alloy. The results of this correlation can be seen in Figure 5. A linear approximation is proposed for the available test results with a very good agreement (R = 0,97). The strain energy density W can be evaluated from the area under the tensile stress– strain curve as:

$$W = \frac{dU}{dV} = \int_0^A s \cdot de \tag{3}$$

where U is the strain energy V the material volume and A the elongation just before fracture. It is reported in the literature [12], that it can be roughly assessed by taking into account the yield strength R_p, tensile strength R_m elongation to fracture A_f, or from even tensile strength and elongation to fracture [13]. The correlation of the plot of Figure 5 supports that strain energy density is more sensitive to the elongation to fracture variations.

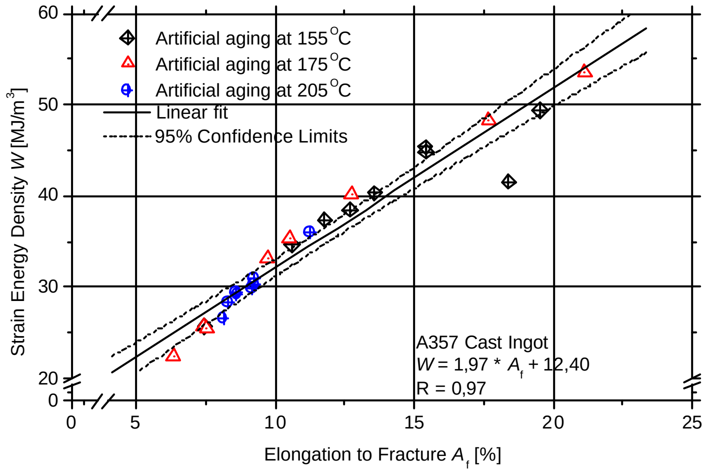
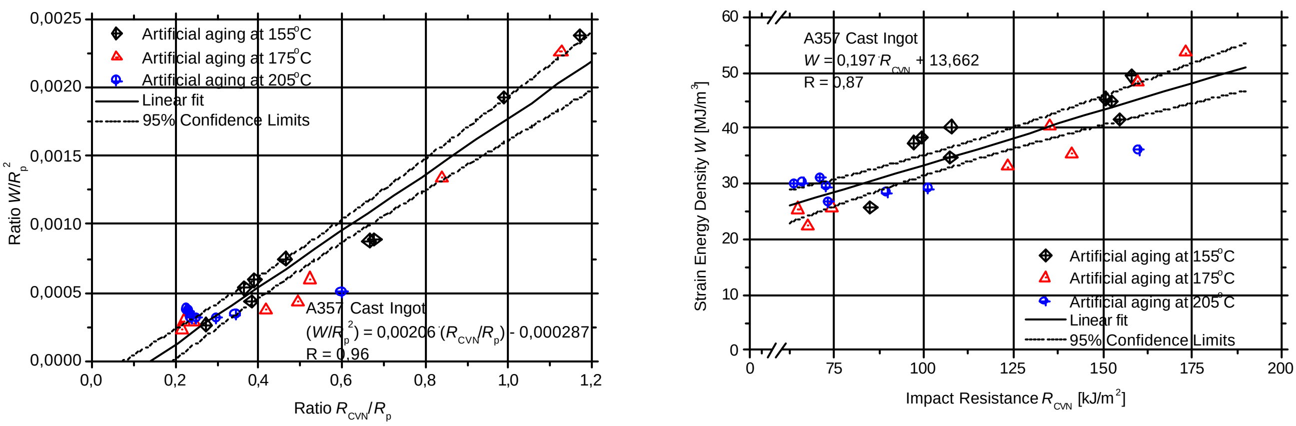


Figure 5. Correlation of the plot of the tensile strain energy density W over the elongation to fracture A_f, for the investigated artificial aging heat treatment conditions of the A357 cast aluminum alloy.

The correlation of impact energy and tensile strain energy density has not been reported in the open literature. Yet, in the early 70's an empirical equation was proposed for both, low-alloyed and austenitic steels, to calculate the alloy's plane strain fracture toughness K_{Ic}, for known Charpy V-notch impact energy W_{CVN} and yield strength R_p values [5]. For these steel alloys, a linear correlation between the ratios $(K_{Ic}/R_p)^2$ and W_{CVN}/R_p was introduced. In analogy to the above observation, in Figure 6a, the ratio W/R_p^2 has been displayed over the ratio R_{CVN}/R_p for the investigated 25 different artificial aging heat treatments of the A357 cast alloy. In the plot, the tensile energy density has been involved instead of the plane strain fracture toughness as according to [6] W is proportional to K_{Ic}^2. The experimental results of Figure 6a may be fitted well by the linear expression:



(a) (b)

Figure 6. Correlation of the plots of (a) the ratio W/R_p^2 over R_{CVN}/R_p and (b) the tensile strain energy density W over the impact resistance R_{CVN} for the investigated artificial aging treatment conditions of the A357 cast aluminum alloy.

$$\frac{W}{R_p^2} = f \cdot \frac{R_{CVN}}{R_p} + g \tag{4}$$

where f = 20,57·10^{-4} m^2/kJ and g = 2,86·10^{-4} MPa^{-1} are empirically derived constants. The standard deviation factor R was calculated to 0,96.

A further simplification represents the plot of the tensile strain energy density over the impact resistance (Figure 6b). This correlation is supported by the experimental observations of Figure 3. The results of Figure 6b were correlated by the linear expression:

$$W_{Ch} = p \cdot R_{CVN} + q, \tag{5}$$

where p = 0,197 k·m^{-1} and q = 13,664 MJ/m^3 are empirically derived constants. The standard deviation factor R decreases from R = 0,96 for eqn.(4) to R = 0,87 for eqn.(5). Yet, given the scatter of the properties of cast alloys, the observed deviations are acceptable. With eqn.(5), the impact test may be exploited to get quantitative information about the material's tensile ductility and toughness.

Strain energy density W is a material property, which characterizes the damage tolerance potential of a material and may be used to evaluate the material fracture under both, static and fatigue loading conditions [6]. Note that energy density may be directly related to the plain strain fracture toughness value K_{Ic} [14,15], which evaluates the fracture of a cracked member under plain strain loading conditions. The quantity dU/dV in eqn. (3) tends to a critical value of energy density W_C as the elongation tends to the elongation A at failure time. According to the works in [14,15], the critical energy density function may be related to the energy density factor S:

$$\left(\frac{dU}{dV}\right) = \frac{S}{r} \rightarrow \frac{S_C}{r_C} \text{ at instability,} \qquad W_C = \frac{S_C}{r_C}. \tag{6}$$

Note that the plain strain fracture toughness value K_{Ic} gives S_C since:

$$S_c = \frac{(1+v)(1-2\cdot v)\cdot K_{Ic}^2}{2\cdot p\cdot E} \tag{7}$$

in which ? and E are the Poisson's ratio and Young's modulus, respectively. The critical ligament size r_C measured from the crack tip is related to the process zone size that has been discussed extensively in the literature. Crack initiation is assumed to prevail when dU/dV -> (dU/dV)$_C$ while the onset of rapid crack propagation is assumed to be reached when S -> S_C. Refer to [14,15] and the references therein for more details, particularly the application of the energy density approach to ductile materials [6]. Substituting the critical energy factor S_C of eqn.(6) to eqn.(7), the material's plain strain fracture toughness becomes a function of the strain energy density:

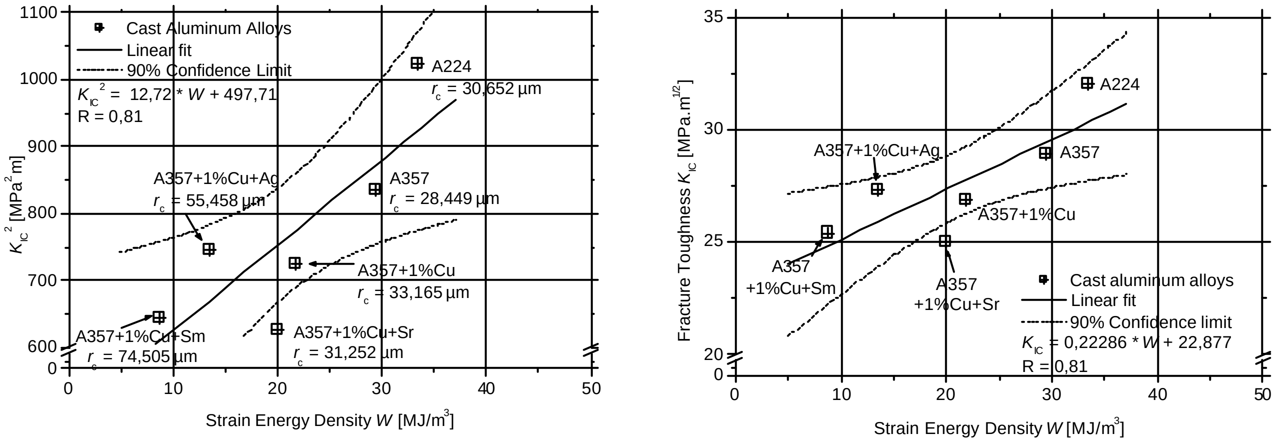
$$K_{Ic}^2 = \frac{2\cdot p\cdot E\cdot r_c\cdot W}{(1+n)\cdot(1-2\cdot n)}. \tag{8}$$

To this end, the values of fracture toughness K_{Ic}^2 and strain energy density W of the investigated cast aluminum alloys had been plotted in Figure 7a. As can be seen, the pairs of their respective values can be linearly fitted with a good approximation (R = 0,81). The pair of values (K_{Ic}^2,W) can be substituted to eqn.(8) and calculate the critical ligament r_C from the crack tip for each alloy, given that the Young's modulus E and the Poisson ratio v values are the same for all the investigated materials. The calculation results are summarized in Table 1, and the calculated ligaments ranged from 28 to 74 µm for the investigated alloys. The high calculated ligament size of both alloys A357+1%Cu+Ag and A357+1%Cu+Sm was attributed to both, high fracture toughness and medium strain energy density values of the respective alloys. Nevertheless, it is the author's opinion that the average ligament size should yield to a fixed value around 30 µm. This ligament size r_C is actually of the order of magnitude of the material's grain size measured in [1].

A more simplified equation to correlate the material's tensile and fracture toughness is proposed in Figure 7b. The results of this Figure were correlated by the linear expression:

$$K_{Ic} = a \cdot W + b, \tag{9}$$

where a = 0,22286 m$^{1/2}$ and b = 22,877 MPa·m$^{1/2}$ are empirically derived constants. The standard deviation of eqn.(9) remains the same (R = 0,81) as of equation proposed in Figure 7a.



(a) (b)

Figure 7. Correlation of the plots of (a) the ratio K_{Ic}^2 over tensile strain energy density W and (b) the plain strain fracture toughness K_{Ic} over strain energy density W for the investigated cast aluminum alloys.

A more accurate expression to correlate the material properties of the investigated materials is proposed in Figure 8 by means of linear fit of the calculated pair of values. Exploiting the eqn.(1) for the case of cast aluminum alloys and by substituting the impact energy W_{CVN} by the strain energy density W, the expression takes the form:

$$\left(\frac{K_{Ic}}{R_p}\right)^2 = c \cdot \left(\frac{W}{R_p}\right)^2 + d \tag{10}$$

where c = 0,611 m and d = 0,005 m are empirically derived constants. The standard deviation of the proposed linear expression is very low (R = 0,95). The use of such an equation may be useful to fast estimate the fracture toughness of a cast alloy, given their tensile properties R_p, and W. Further examination for the validity of eqn.(10) for other cast aluminum alloys should be made.

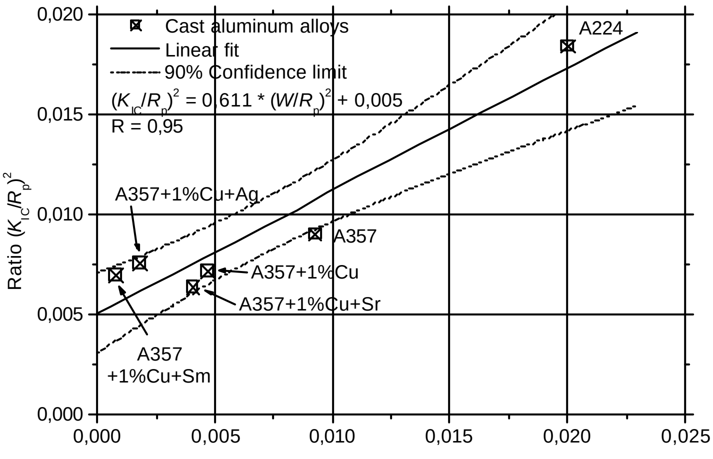
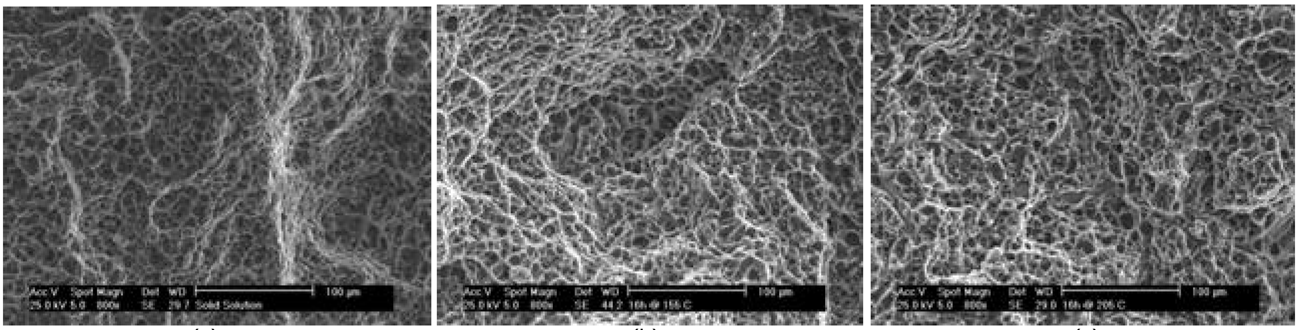


Figure 8. Correlation of the plot of the ratio $(K_{Ic}/R_p)^2$ over the ratio $(W/R_p)^2$ for the investigated cast aluminum alloys.

The performed fractographic analyses are supporting the physically arbitrary correlation of tensile strain energy density and impact resistance. Fracture surfaces from tensile and impact specimens obtained by using SEM are compared in Figures 9 and 10. The specimens in Figures 9a and 10a refer to solid solution, in Figures 9b and 10b to underaging (16 hours at 155^{o}C), and in Figures 9c and 10c to peakaging conditions (16 hours at 205^{o}C). The fracture surfaces for the tensile specimens are presented in Figures 9a to c. For all aging conditions investigated, morphologically similar, rough fracture surfaces including large dimples were observed. These surfaces correspond to ductile fracture and imply the same void - coalescence fracture mechanism. The respective fracture surfaces for the impact specimens are presented in Figures 10a to c. As it can be seen, the morphology of the fracture surfaces of the impact specimens does not differ from the fracture surface morphology observed for the tensile specimens, despite the five order of magnitude difference in the rate of mechanical load application.

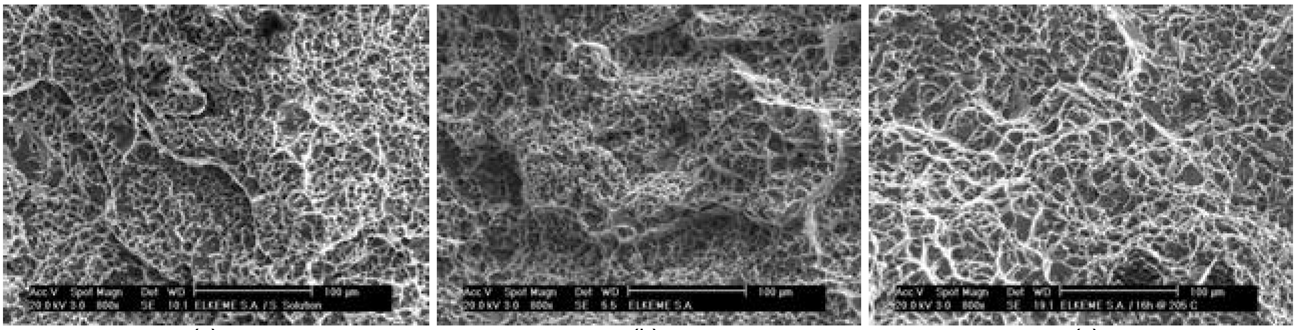
Table 1. Calculated values of the critical ligament size r_C of eqn.(8).

Material	Critical ligament size r_c [µm]
A357	28,449
A357+1%Cu	33,165
A357+1%Cu+0.7%Ag	55,458
A357+1%Cu+0.5%Sm	74,505
A357+1%Cu+Sr	31,252
A224	30,652



(a) (b) (c)

Figure 9. Fracture surfaces of cast ingot A357 tension specimens for (a) solid solution, (b) aging for 16 h at 155°C and (c) aging for 16 h at 205°C.



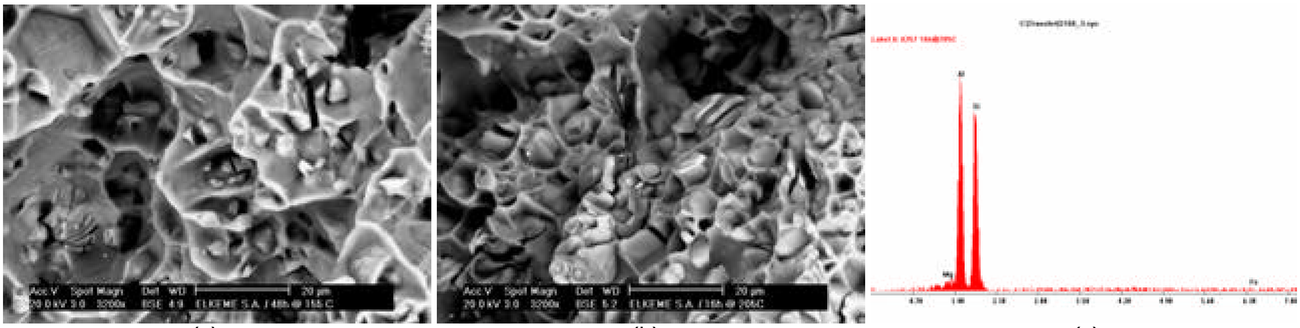
(a) (b) (c)

Figure 10. Fracture surfaces of cast ingot A357 impact specimens for (a) solid solution, (b) aging for 16 h at 155°C and (c) aging for 16 h at 205°C.

In Figure 11, micrographs of the fracture surfaces of the impact specimens aged for 48 hours at 155^{o}C and 16 hours at 205^{o}C, respectively, are presented by involving a higher SEM resolution. In the Figures, additionally to the dimples, same micro-cracks may be observed as well. Using the EDX analysis, it was found that the cracked areas all over the specimen contain high Si quantities [13]. In the A357 alloy, high quantities of Si may be observed only in the Si particles; they are preferably located at the grain boundaries of the Al-phase. This observation is indicative for an intercrystalline fracture mode and is consistent to previous investigations [16,17].

Conclusions

Correlations of the fracture related mechanical properties that are widely used for the characterization of the cast aluminum alloys had been proposed. The established correlations, which are well supported by the performed experiments, allows to estimate the tensile ductility and toughness of the A357 cast aluminum alloy from the Charpy impact test, or to estimate its plain strain fracture toughness from the tensile toughness values.



(a) (b) (c)

Figure 11. Fracture surfaces of cast ingot A357 impact specimens for (a) aging for 48 h at 155°C, (b) aging for 16 h at 205°C and chemical analysis of the latter heat treatment condition.

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