Evaluation of fracture toughness in HPDC aluminium alloys to estimate crashworthiness in automotive parts

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Aluminum high pressure die casting (HPDC) alloys are widely applied in the automotive sector. The constant needs for lightweight materials open a new opportunity for Al castings in structural applications in vehicles. New HPDC Al alloys with high ductility are available and are potential candidates for Body-in-White applications with crash requirements. Therefore, an assessment of the crashworthiness of these materials is required. In previous publications, the authors demonstrated that the fracture toughness, measured in the frame of fracture mechanics can be related to crash resistance in high strength steels and aluminum sheets. In this context, the characterization of the fracture toughness of two aluminum alloys with different ductility (AlMg4Fe2, AlMg4Fe2Zn3) was assessed following linear elastic fracture mechanics (LEFM), in terms of K_{Ic} and elastic-plastic fracture mechanics (EPFM), in terms of the essential work of fracture, w_e. The results show that LEFM is not suitable to evaluate the fracture toughness of HPDC alloys with a significant amount of plasticity. On the other hand, it is showed that we describes the fracture toughness for high ductility alloys and it is here proposed as a material property to predict the crashworthiness of ductile HPDC alloys.

KEYWORDS: ALUMINUM, HIGH PRESSURE DIE CASTING, CRASHWORTHINESS, FRACTURE TOUGHNESS, EWF

INTRODUCTION

The electrification of cars, and the control on the CO2 emission and fuel consumption are pushing automakers toward adopting lighter structures. New materials and forming processes have been developed in the last years to meet these demands, as advanced high strength steels (AHSS) and high strength aluminum alloys [1]. Aluminum high pressure die casting (HPDC) alloys are widely applied in the automotive sector. Their ability to create lightweight parts without sacrificing the strength, and their distinctive features such as corrosion resistance, excellent electrical conductivity and high stability for complex shapes make them good candidates for powertrain parts, body-in white and chassis. Recent developments in HPDC have provided new opportunities for structural parts in electrical vehicles [2, 3, 4]. However, their efficient implementation depends on the ability of the car industry to optimize the fatigue and fracture performance.

Crashworthiness is one of the relevant material properties for lightweight construction of structural automotive parts. However, it is a complex property to measure. It

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is usually measured with expensive and time-consuming tests, which often do not inform about the intrinsic material resistance to crash. Thus, Al manufacturers and carmakers are constantly looking for laboratory scale tests to characterize the crash behaviour and the fracture resistance. The work of Frómeta et al. showed that tensile properties such as the fracture elongation or the energy under load-displacement curve failed to provide a good characterization of the crashworthiness of AHSS [5]. Alternatively, some works in AHSS pointed that the fracture toughness, measured within the framework of fracture mechanics, is the relevant material property to describe the fracture resistance in crack related processes, like edge-cracking and crash tests [6,7]. More recently the work of Pujante et al. also showed that fracture toughness could be used to rank crashworthiness in high strength Al sheets [8]. Thus, fracture toughness emerges as a relevant material property to estimate crash resistance. The fracture toughness evaluation of thin parts, as thin sheets used in chassis and Body-in-White parts or thin-walled components obtained by HPDC, is experimentally challenging, because fracture toughness is thickness dependent. Specimen thickness defines if plain strain or plain stress fracture conditions prevail. Most of the standardized tests are defined for thick specimens, under plane strain condition. In addition, the lack of experimental standards to evaluate the fracture toughness when the thickness requirement is not fulfilled hinders the proper knowledge of their fracture resistance. In response to this need, the essential work of fracture approach was introduced in the frame of EPFM to determine the fracture toughness for ductile metal sheets under plane stress state [9,10].

This paper aims to assess the evaluation of fracture toughness of two HPDC aluminium alloys with different ductility range, with the objective to define the best approach to estimate crashworthiness at lab scale. Two fracture toughness approaches based on LEFM (K_c) and EPFM (w_e) were presented and discussed.

THEORETICAL PRINCIPALS

LINEAR ELASTIC FRACTURE MECHANICS, K_{Ic}

The plane strain fracture toughness, K_{Ic}, is the crack-extension resistance under mode I and linear-elastic conditions at the onset of 2% of the crack extension. The test procedures to measure it is defined in ASTM-E399 standard. The method involves testing fatigue pre-cracked notched specimen. The most used specimens are C(T) and SE(B). The load-displacement curve is recorded during the test. P_Q corresponds to 2% apparent increment of crack extension and established by a 0.95 deviation from the linear portion of the recorded curve as indicated in Fig.1. From the P_Q value and the measured crack length for each test, the conditional fracture toughness K_Q is calculated using the equation:

$$K = \frac{PQ\sqrt{\pi a}}{t_0 \cdot W\sqrt{1-\frac{a}{b}}}\left[1.122 - 0.561\left(\frac{a}{b}\right) - 0.205\left(\frac{a}{b}\right)^2 + 0.471\left(\frac{a}{b}\right)^3 - 0.190\left(\frac{a}{b}\right)^4\right] \quad \textbf{Eq (1)}$$

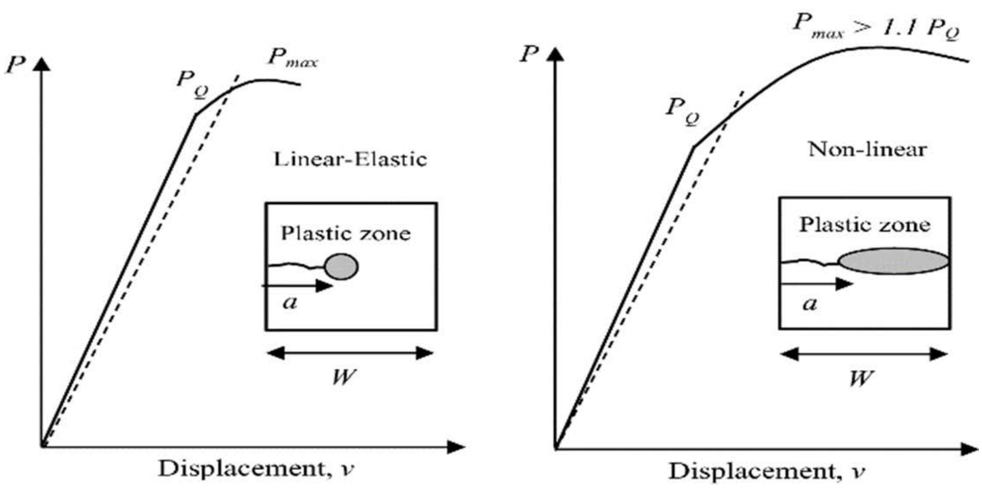

Fig.1 - P_Q determination as described in ASTM-E399.

where a is the crack length, t_0 is the sheet thickness, W is the specimen width and b is the half of specimen width. Since K_{Ic} is thickness dependent i.e., toughness decreases with increasing the specimen size until reaching a plane strain mode, the following validity requirements are imposed to ensure that the measured K_{Ic} is thickness independent.

$$to, a > 2.5 \left(\frac{K_Q}{\sigma_{ys}}\right)^2 \quad \textbf{Eq (2)}$$

$$P_{max} < 1.1P_Q \quad \textbf{Eq (3)}$$

where σ_{ys} is the 0.2 % offset yield strength and P_{max} is the maximum load recorded during the test. The second requirement, Eq (3) is to ensure that the non-linearity observed corresponds to the crack initiation and not to large plastic zone in the ligament [9].

ELASTIC-PLASTIC FRACTURE MECHANICS, w_e

The essential work of fracture (EWF) concept proposes that the work performed at the crack region of a ductile material fractured under elastic-plastic condition and plane stress state (w_f) is proportional to the ligament length (l_0) and can be separated into two parts: (i) the essential work of fracture performed in the inner fracture process zone (w_e) and (ii) the non-essential work of fracture performed in the outer fracture process zone (w_p) [6]. The total work of fracture (w_f) can be written then as:

$$W_f = Bl_0w_e + \beta B{l_0}^2w_p \quad \textbf{Eq (4)}$$

where β is a constant, which depends on the shape of the plastic region. Thus, by testing a series of geometrically similar specimens, the separation of the two energies is possible. Eq (4) is valid only if the ligament between the two notches is fully yielded prior to crack initiation and the plastic zone is uncontained within the ligament Fig.2. The test is usually performed on double edge notched (DENT) specimens.

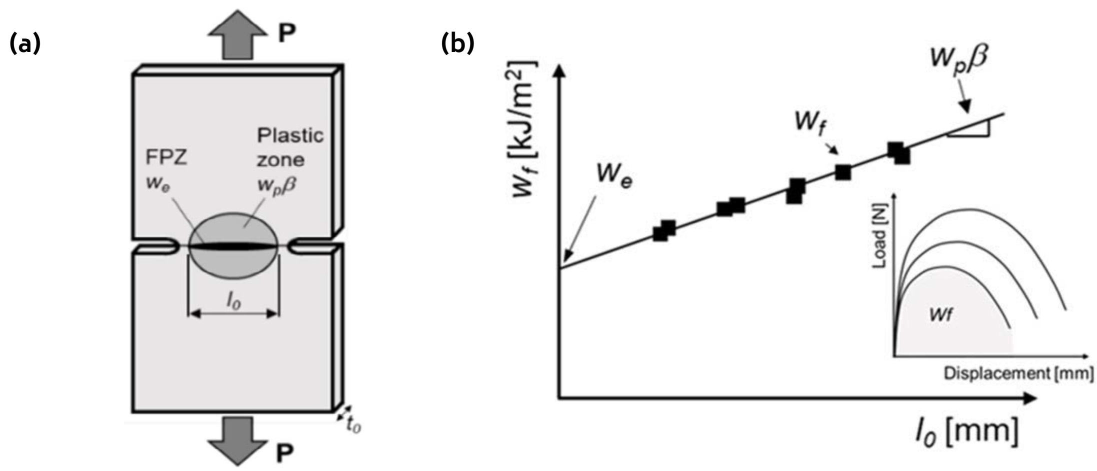

Fig.2 - (a) DENT specimen ;(b) Linear relationship between total specific work and the ligament length and determination of w_e at the y-axis intercept.

MATERIALS

Two high performance HPDC Al alloys were used in this study: AlMg4Fe2 (Castaduct-42) and AlMg4Zn3Fe2 (Castaduct-18) alloys. The chemical composition and the tensile properties are listed in tables 1 and 2.

Tab.1 - Chemical composition (wt%) of Castaduct-42 and Castaduct-18. The balance in Al.

Alloy		Si	Fe	Mg	Cu	Mn	Zn	Ti
Castaduct-42	Min.		1.5	4.1				
	Max.	0.2	1.7	4.5	0.2	0.15	0.3	0.2
Castaduct-18	Min.		1.5	4.1			3.3	
	Max.	0.2	1.7	4.5	0.2	0.15	3.6	0.2

Tab.2 - Tensile properties of Castaduct-42 and Castaduct-18.

Alloy	Yield strength [MPa]	Tensile strength [MPa]	Total Elongation [%]
Castaduct-42	121	259	19.4
Castaduct-18	187	311	6.9

METHODS

DENT specimens of 120 x 60 x 3 mm (H x W x T) were used for the LEFM tests. The edge notches were machined by electrical discharge machining (EDM) then followed by a fatigue pre-crack of 1.5mm. The ligament length is about 14 mm (a/b=0.8) as indicated in Fig.3. The test was performed at a quasi-static strain rate of 1 mm/min with a gauge length of 25mm.

The EWF experimental test was carried out on a batch of specimens with a ligament length varying between 6 and 14 mm, 2 samples were used for each ligament length. The test conditions, fatigue pre-crack and gauge length were the same as for LEFM tests. The values of w_f were obtained by integrating the area under the load displacement curve and dividing by the cross-section area. w_e was determined from the extrapolation of w_f vs l_0 data to zero ligament length. Details about the experimental procedure are detailed in previous works [4,5,7].

The simulation of the experimental test has been made by finite element (FE) code" ABAQUS". Due to the symmetry in the geometry and loading condition, only 1/8th of the geometry has been modeled. To reproduce the real behavior of the material, the true stress-strain curve obtained from a tensile test was introduced in the model. A 3D eight-nodes element was used for the FE calculation. For the crack tip, singular elements were used and a finer mesh to improve the accuracy. The analysis was performed in the elastic regime and several contours were employed around the crack tip to calculate the energy release rate.

RESULTS AND DISCUSSION

EXPERIMENTAL RESULTS

Values of 13 MPam$^{1/2}$ and 18 MPam$^{1/2}$ were calculated for Castaduct-42 and Castaduct-18 respectively (Fig.3). The validity requirements were then checked for both alloys. The Castaduct-18 fulfilled the first requirement as (P_{max}/P_Q=1.1). On the other hand, the ratio exceeded 1.1 for the Castaduct-42 (P_{max}/P_Q=1.3). Consequently, K_Q is meaningless and not giving a toughness value for the Castaduct-42. LEFM is then applicable only in the case of Castaduct-18. EPFM should be assumed in the more ductile alloy. To verify if K_Q is equivalent to K_{Ic} in the case of Castaduct-18, the specimen size requirement must be met. A value of 25.8 mm of thickness should be satisfied for this alloy, much higher than the thickness of the specimens (3 mm). Therefore, K_Q cannot be considered as K_{Ic} , then it is the fracture toughness for the tested thickness.

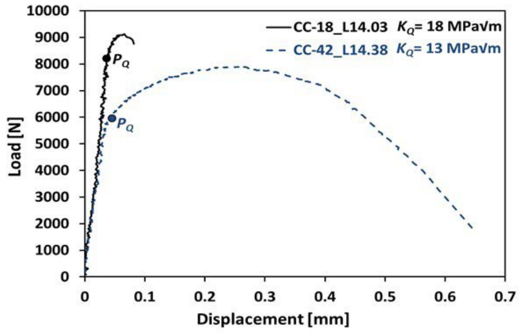

Fig.3 - P_Q determination from load-displacement curves of Castaduct-18 and Castaduct-42.

Typical load-displacement curves of the DENT specimens obtained from the EWF experiments are shown in Fig.4. It can be observed that the curves are self-similar for both alloys. The Castaduct-42 showed a larger area under the load displacement curve compared to Castaduct-18, which is consistent with their higher ductility. On the other hand, the Castaduct-18 reached higher maximum load. The sharp drop after the maximum load indicates a more brittle fracture behaviour, which is also consistent with their low ductility.

Fig.4 shows the evolution of w_f vs l_0 for both alloys. It is observed that w_f linearly scales with l_0 in the case of Castaduct-42, which indicates that the premises of energy separation given by the EWF protocol are valid. The measured toughness in terms of w_e, is 36 kJ/m². However, w_f does not change for different specimens in Castaduct-18, which means that the EWF approach is not valid for the case of Castaduct-18 alloy.

Digital Image Correlation (DIC) technique was used to examine the evolution of the plastic zone in the ligament zone during the fracture process. DIC results confirmed that the complete yielding condition, necessary for the validity of the EWF method, was extensive and proceeded the crack initiation in the case of Castaduct-42 but fails for Castaduct-18. Thus, EPFM does not describe the behaviour of low ductility alloys.

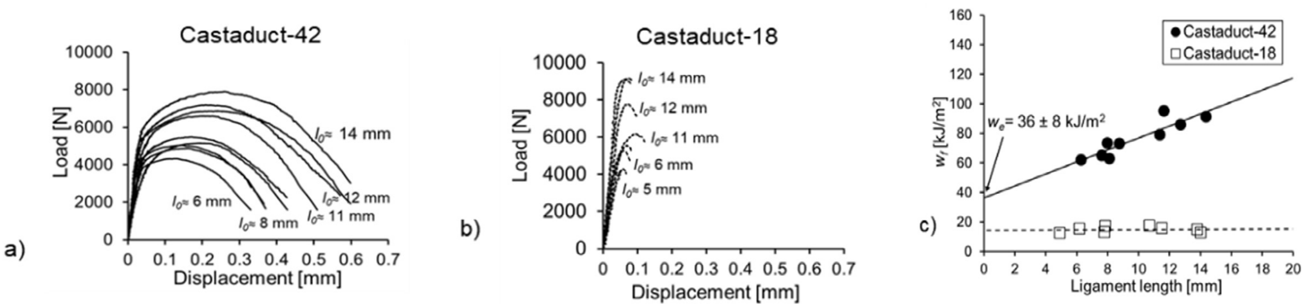

Fig.4 - Load-displacement curves and EWF for Castaduct-18 and Castaduct-42.

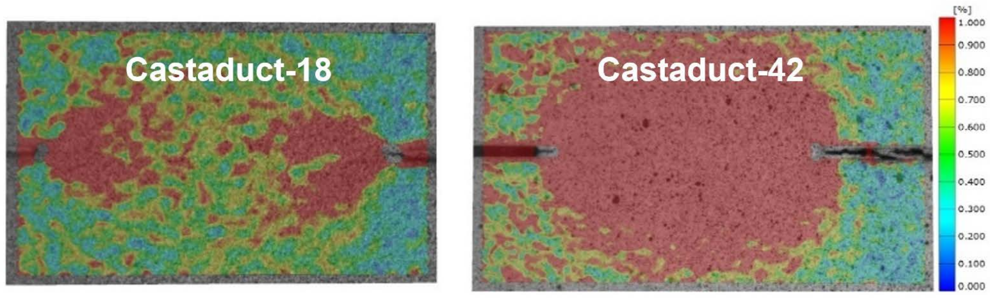

Fig.5 - DIC measurements of the plastic zone ahead of the crack tip for the two studied alloys.

NUMERICAL RESULTS

Since the conditional toughness K_Q is meaningless for Castaduct-42 alloy, only Castaduct-18 is modelled. The Von Mises stress distribution is shown in Fig.6. The low degree of plasticity in the ligament zone can be seeing. Several contours were used for the calculation of K_I. It can be seen from table.3 that the last several contours give independent results. The K_I extracted from the FE model agrees well with the value obtained in experimental LEFM tests (table 4).

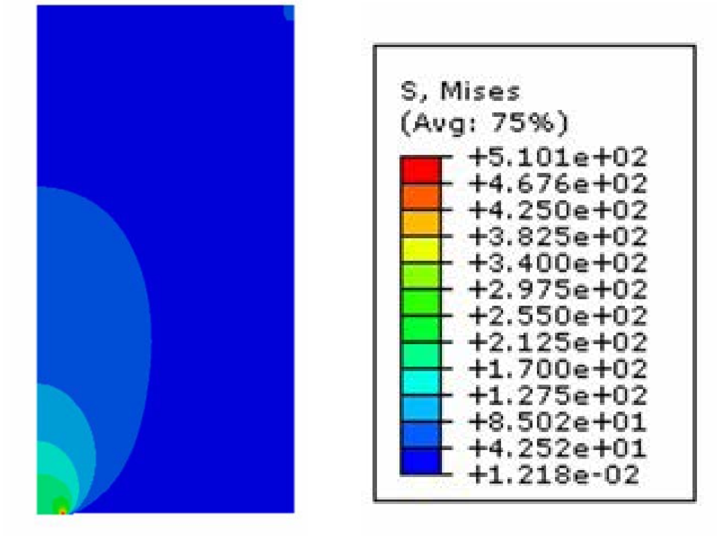

Fig.6 - Von Mises stress distribution at the crack tip.

Tab.3 - Stress intensity factor in mode I (K_I) extracted form FE modelling at different contours.

K_I [MPa.mm $^{1/2}$] Castaduct-18						
Position	contour 1	contour 2	contour 3	contour 4	contour 5	contour 6
Middle of the crack font	606.7	629.8	632.4	633.1	633.3	632.7

Tab.4 - Comparison between experimental and FE modelling results.

	Experimental (MPa.m$^{1/2}$)	Numerical (MPa.m$^{1/2}$)
Castaduct-18	18	20

SUMMARY AND CONCLUSIONS

- The development of a significant amount of plasticity at the crack tip in the case of the ductile HPDC alloy (Castaduct-42) restrained the use of LEFM. Thus, EPFM method should be used for high ductility alloys.
- LEFM can be applied to low ductility HPDC alloy (Castaduct-18).
- The characterization of fracture resistance of the HPDC Al alloys developed for crash applications must be done in the frame of EPFM. In this sense, the Essential Work of Fracture methodology gives reliable values of fracture toughness. It is proposed as a testing method to estimate crashworthiness for HPDC alloys with high ductility.
- The numerical verification of the path independence exhibits results that confirm the robustness of the implementation of LEFM toughness.

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