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On the ductility potential of cast Al–Cu–Mg (206) alloys

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ABSTRACT

The yield strength–elongation relationship in cast Al–Cu–Mg alloys (206) castings has been investigated by analyzing 13 datasets from the literature on premium quality castings. The data representing the elongation for a given yield strength have been found to fall within an envelope, the top limit of which represents the ductility potential of Al–Cu–Mg alloy castings. Moreover, using the fracture toughness equation by Hahn and Rosenfield, estimated intrinsic fracture toughness values have been found to be consistent with the data reported in the literature.

1. Introduction

Aluminum–copper casting alloys offer excellent mechanical properties and good corrosion resistance in certain tempers. In the Al–Cu casting alloy family, the 201 alloy is the strongest, due to the Ag additions which result in the precipitation of the Ω phase and consequently greater response to age hardening. This enhancement in strength with the Ag addition is also accompanied with an increase in cost of the alloy. That is why the 206 alloy was developed in 1970s as an alternative to 201 alloy to preserve the high ductility and strength combination, but without the expensive Ag addition in 201.

Since its inception, the 206 alloy has been rarely used in critical applications because of casting problems mainly associated with hot tearing. In addition, there are concerns about the variability in properties, especially in elongation and fatigue life. The high level of variability is a consequence of structural defects in castings, i.e., pores and oxide bifilms, which degrade mechanical properties; they cause premature fracture in tension [1,2] and fatigue [3], resulting in low ductility, tensile strength and fatigue life [4]. In addition, the presence of major structural defects decreases the work hardening potential in tension [2,5] and also results in increased variability in properties, as evidenced most notably by lower Weibull moduli [6–8]. Hence minimization and even elimination of the structural defects is vital for wider use of aluminum castings in structural applications in automotive industry.

Foundry engineers striving to resolve quality concerns in aluminum castings, such as low ductility, often try to change the heat treatment procedure, assuming that ductility can be increased mainly by compromising strength. These efforts are usually ineffective unless the root cause of low ductility, i.e., structural defects, is addressed. Hence when oxide bifilms and porosity are present in castings, it is at best inefficient and at worst fruitless to approach the problem from a ductility–strength compromise point of view.

In the quest for improved properties it is helpful for the foundry engineer to have a metric to measure the degree of improvement that they make. The so-called quality indices developed over the years are intended to serve this need. Among the quality factors developed so far, only the ones by Cáceres [9] and Tiryakioğlu et al. [10] supply a measure in terms of the ratio of the current to achievable ductility. Both indices determine the achievable (or target) quality from the work hardening characteristics of the specimen. This approach, however, underestimates the true ductility potential of the alloy [11] because structural defects decrease the observed work hardening rates significantly [2,5]. Therefore a more fundamental approach is needed to estimate the true ductility potential of cast aluminum alloys. Such an approach is reported in this study.

2. Background

Fracture-related properties of castings are controlled by the structural defect or concentration of defects that leads to the largest stress concentration. The point of largest stress concentration con-

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stitutes the weakest link, which is modeled and assessed by the Weibull distribution [12]. In Al–Si alloy castings, tensile strength, elongation-to-fracture (e_F) and fatigue life are properties related to fracture initiated at the weakest link, and therefore are expected to follow a Weibull distribution, as shown in the literature [3,13,14]. Mi et al. [6] conducted experiments on Al–4.5 wt.%Cu alloys and found that the Weibull modulus, a measure of reliability, decreases with increasing level of entrainment of surface oxide films. Therefore there is strong evidence that the mechanical properties of cast Al–Cu alloys are governed by the size distribution of defects, with the largest defects resulting in premature failure. In contrast, yield strength (σ_Y) is not expected to follow a Weibull distribution because the weakest link concept does not apply. The material at and around the largest stress concentration yields before the rest of the material, flows plastically and work-hardens, making up, at least partially, for the loss in resistance to deformation. Thus yield strength should be relatively insensitive to defects, as is commonly observed.

Din et al. [15] investigated the change in the tensile properties of A206 and A201 castings with artificial aging time. The authors found linear relationship between elongation and yield strength, especially in the underaged condition. Cáceres et al. [16], using the same data, demonstrated that the quality index that he developed previously [9] can be applied to cast Al–Cu alloys. Cáceres' quality factor, Q_c, is a ratio of e_F to elongation expected of the specimen if it were free from structural defects, $e_{F(e)}$:

$$Q_c = \frac{e_F}{e_{F(e)}} \tag{1}$$

Cáceres assumed that cast aluminum alloys follow the well-known Ludwik–Hollomon equation:

$$\sigma = C\varepsilon_p^n \tag{2}$$

where σ and ε_p are true stress and true plastic strain, respectively, C is the strength coefficient and n is the strain hardening exponent. The true plastic strain at the onset of necking (ε_u), i.e., true uniform strain, can be shown to be equal to n, when the material deforms following Eq. (2). In Al–7%Si–Mg aluminum aerospace castings, McLellan [17] observed that fracture takes place with almost no necking. Consequently, Cáceres estimated that $e_{F(e)} \approx n$.

In the development of a new quality index based on energy absorbed by a specimen prior to fracture, Tiryakioğlu et al. [10] estimated $e_{F(int)}$ using work hardening characteristics, namely the Stage III Kocks–Mecking work hardening model [18,19] and the Voce equation [20]. The author, however, determined that the late stages of work hardening, where the Considere criterion is met, cannot be estimated from early stages [11]. Hence, if a specimen fractures prematurely due to the presence of structural defects, such as porosity and/or oxide bifilms, the extrapolation of work hardening characteristics to higher strains underestimates elongation. This is partially because structural defects reduce the observed work hardening rates significantly [2,5]. Tiryakioğlu et al. also introduced an empirical equation to predict expected elongation as a function of yield strength:

$$e_{F(e)} = \beta_0 \exp(-\beta_1 \sigma_Y) \tag{3}$$

Nyahumwa et al. [21,22] introduced the concept of fatigue life potential and applied it to an Al–7%Si–Mg alloy. The authors argued that although structural defects would almost always dictate the fatigue life, occasionally a specimen would be obtained without a defect, i.e., without the weakest link. Such data can be obtained when molten metal is treated carefully and the filling system for the casting is designed correctly. Such outliers, then, can be used as a measure of the fatigue life potential or intrinsic fatigue life of the alloy. Nyahumwa et al. showed that the fatigue life of castings that are free from structural defects is several orders of magnitude higher than those with structural defects.

Mechanical property data from 206 castings are analyzed to find trends in *maximum* values. Those data are then analyzed to (i) estimate the ductility potential of the 206 alloy and (ii) determine whether there is any relationship between fracture toughness and tensile properties of the 206 alloy.

Table 1
The datasets used for yield strength–elongation relationship.

Dataset	n_s	Reference	Alloy	Notes
e1	53	[1]	A206	Ingot, some HIPed
e2	8	[23]	A206	Permanent mold castings
e3	192	[24]	B206	Permanent mold castings
e4	20	[25]	B206	Permanent mold castings
e5	6	[26]	A206	Sand castings
e6	10	[27]	A206	Chilled plaster mold
e7	38	[28]	A206	Sand castings
e8	4	[29]	A206	Investment castings
e9	16	[30]	206, A206	Permanent mold
e10	58	[31]	A206	Sand castings
e11	7	[32]	A206	Premium castings
e12	6	[33]	206	Sand cast test bars
e13	13	[34]	A206	Premium casting

3. Data analysis and discussion

Bivariate data for yield strength–elongation (13 datasets) were analyzed in this study. Details of the datasets are provided in Table 1 where n_s represents the number of data. A total of 431 tensile data were included in this analysis.

The σ_Y–e_F data from the sources shown in Table 1 are presented in Fig. 1. Note that yield strength is plotted in the x-axis because of its relative insensitivity to the presence of structural defects for reasons explained above. In Fig. 1, the vertical scatter is mostly due to the varying structural quality of the specimens, as shown previously for cast Al–Cu [1,5] and Al–Si alloys [35,36].

Note in Fig. 1 that the highest points follow a curvilinear trend. The curve drawn in the figure follows Eq. (3):

$$e_{F(int)}(\%) = 71 \exp(-0.004\sigma_Y) \tag{4}$$

It is significant that maxima of data taken from different sources indicate such a consistent trend with yield strength. To the authors' knowledge, it is the first time that the ductility potential of the 206 alloy is reported, especially with such a large number of data.

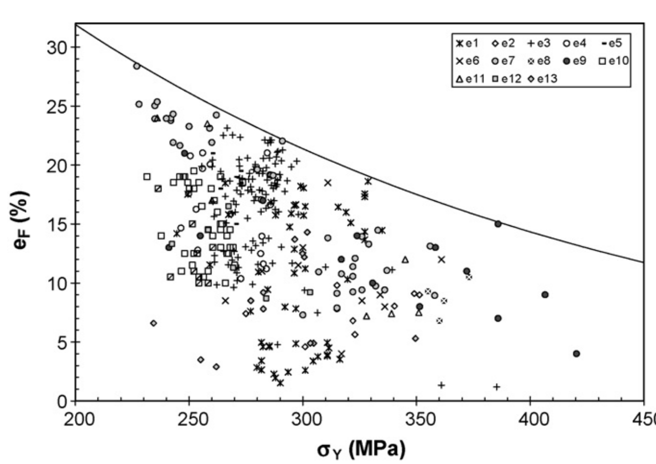

Fig. 1. Yield strength–elongation relationship in 206 alloy castings.