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Generation of quality maps to support material selection by exploiting the quality indices concept of cast aluminum alloys

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Abstract

The use of quality indices of cast aluminum alloys to support material selection by means of generation of quality maps was investigated. The quality indices are methods for quality evaluation of cast aluminum alloys that evaluate the material on the basis of its mechanical performance. Quality maps were generated to support the material selection, on the basis of all proposed quality indices, devised for the evaluation of cast aluminum alloys to be used in aircraft applications. Produced quality maps provide the design engineer a tool to estimate a quality plateau, where lies all the candidate materials to be used for the specific application. Quality maps allow for comparison with all aluminum alloy systems. They also allow for a systematic assessing of the effect of chemical composition, solidification rate and heat treatment on the mechanical performance of the material. Use of such quality maps enables the design engineer to quick select the candidate materials of high quality (optimized mechanical performance) in order to maximize the quality of the structure.
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1. Introduction

In most cases, the general term "quality" for a engineering structure includes a number of several demands/restrictions; e.g., ability of the structure for safe service, to meet the defined performance, to meet specific operating and appearance specifications. Together with the cost, economy of operation, warranty and reputation of manufacturer are important bearing on what each one picture as "quality". Each of the above parameters possess a specific weight in the engineer's judgment, thus making the whole evaluation of the quality of the structure a matter of empiricism and subjectivity. Quality is not an absolute; It is a diamond with many facets.

During the design phase of structural parts, certain requirements in mechanical properties arises, which differs according to the in service mechanical application. Therefore from the design point of view, the quality of an alloy is correlated to whether the alloy has the required mechanical properties for the safe operation of the structural part. The tensile strength and ductility of the material are essential parameters for the characterization of the quality of the material. In aeronautical design structure, fracture toughness of material is also taken into account; due to very low safety factor of the whole structure, the scatter of the mechanical properties is also very important.

The recent advancements on understanding the background physical metallurgy of the age-hardened aluminum alloys [1–4], allow, by the proper selection of chemical composition, solidification rate and heat treatment, to balance tensile strength against ductility, such as to "tailor", within certain material dependent ranges, the material's mechanical properties to the design office requirements. This potential is reflected to the levels of values of the adjustable properties, the width of the range of adjustable properties, the "cost" on strength when "buying" ductility or vice versa, the ease on tailoring the alloy properties to a specific

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combination, etc. The above holistic view of evaluation of mechanical performance of cast aluminum alloys may be expressed through the proper involvement and interpretation of quality indices as they have been proposed in [5–9]. For completeness, the quality indices will be described shortly. The expressions used to evaluate the quality indices are presented underneath, and in the chronological order of appearance in the literature.

2. Quality indices

In 1980, French researchers [5] proposed for the cast aluminum alloy A357 (Al–7Si–Mg) the quality index Q, that takes into account the tensile properties tensile strength R_m and elongation at fracture A_f in the equation:

$$Q = R_m + d \cdot \log_{10}(A_f). \tag{1}$$

The exploitation of the above Eq. (1) to other alloy systems than Al–Si–Mg has not been always manageable. Din et al. in [6], proposed the following expression for experimental data based on Al–Cu alloys:

$$Q_R = R_p + m \cdot A_f, \tag{2}$$

where R_p stands for yield strength and m for an alloy dependent constant with values of 7.5–13 for the Al–Cu alloys. If the Eq. (2) is applied to Al–Si–Mg alloys, the m constant takes the value of 50.

The quality index Q lacked a proper theoretical grounding. The physical basis of Eq. (1) has been studied by Caceres [7] who used the work hardening characteristics of the Al–7Si–Mg alloys to estimate the elongation at fracture A_f of a specimen. The quality index Q_C has finally become a function of the material's yield strength R_p [10]:

$$Q_C = R_m + 0.4 \cdot R_p \cdot \left(\frac{E}{a \cdot R_p}\right)^n \cdot \log(A_f). \tag{3}$$

E is the Young's modulus, n the strain hardening exponent and a a scale factor of order 1.

The index Q_D, [8], evaluates the quality as the potential of the alloy for mechanical performance. This evaluation takes into account the balance between the strength and ductility and also the scatter of mechanical properties of the alloy under evaluation. The material properties used in the Q_D is yield strength R_p and strain energy density W; they were selected to fit the aeronautic design properties prerequisites. The index Q_D is the product of coefficient K_D and quantity Q_0. Coefficient K_D takes into account the scatter in mechanical properties and Q_0 takes into account the average mechanical properties of the materials in the equation:

$$Q_0 = R_p + 10 \cdot W. \tag{4}$$

The quality index Q_D of an alloy is determined as the mean value of Q_{Di} values out of a number of k investigated specimens:

$$Q_{Di} = K_{Di} \cdot Q_{0i} = \left(\frac{R_{pi}}{R_{pmax}} + \frac{W_i}{W_{max}}\right) \cdot (R_{pi} + 10 \cdot W_i). \tag{5}$$

The indices i and max refer to the R_p and W values derived for a specific specimen i and the maximum values derived for R_p and W out of k investigated specimens, respectively.

Tiryakioglou et al., [9], proposed the quality index Q_E, which is built on the concept that energy absorbed is directly related to the effective crack length produced by a discontinuity. Actually, Q_E represents the fraction of the maximum strain energy density that is absorbed by the specimen before failure occurs. The quality index Q_E was defined as:

$$Q_E = \frac{W}{W_c}, \tag{6}$$

where W is the strain energy density of the material, and W_c is a fixed value of strain energy density of the "ideal" alloy modification with no structural discontinuities.

3. Experimental procedure

Tensile test results had been taken by [3,8,11–13] to investigate the adaptability of quality indices to cast aluminum alloys. The experimental effort focus on three points; to generate quality maps of cast aluminum alloys from (i) different series, (ii) the same series and minor variations in chemical composition, and (iii) the same series and variations in heat treatment.

For the first two points, an extensive database of tensile tests was created at the framework of BRITE-EURAM Project ADVACAST [14]. The produced materials were from the systems 2xx (Al–Cu), 3xx (Al–Si–Mg), and 7xx (Al–Zn–Cu–Mg), mainly being used in the aeronautics. The alloys had been produced using the patented casting process Sophia [15] and for comparison, the conventional investment casting process. In the following, S will refer to Sophia and C to conventional casting process. The alloys have been casted in form of plates with different thickness, and flat and round specimens were machined from the plates. The flat specimens have been machined from the thin parts of the plates, while the round from the thick. Flat and round specimens of the same material have been considered separately as different test series. Details about the casting process, machining, tensile testing and evaluation can be found in [8,11,16]. For the wide spread use of the quality index Q_D and the exploitation of the quality maps, extensive databases on mechanical properties of cast aluminum alloys [3,13] have been also used. As strain energy density W usually is not available in material databases, it has been calculated using approximate expressions developed in [17]. For the third point, different artificial aging heat treatment have been applied to the widely used in the aircraft industry A357 alloy. The tensile tests results has been taken from [12].

4. Quality maps

The concept of quality maps for supporting material selection has been introduced since several decades and

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