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Definition of Quality in Cast Aluminum Alloys and Its Characterization with Appropriate Indices

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In this paper, the issue of "quality" of cast aluminum alloys from various viewpoints is interpreted. Many methods to characterize the quality of materials are available; the methods used currently for the quality evaluation of cast aluminum alloys include nondestructive testing, characterization of the microstructure, and mechanical testing. With regard to mechanical testing, a number of quality indices have been devised to evaluate and characterize the quality of cast aluminum alloys. As these quality indices use different mechanical properties for the quality evaluation, they are expected to lead to different results. In this work, the application of proposed quality indices and their suitability is discussed for a number of situations, including minor variations in chemical composition, different solidification rate, solid solution and artificial aging heat treatments.

Keywords cast aluminum alloys, mechanical performance, microstructure, non-destructive testing, quality

1. Introduction

The matter of quality of a structure existed in the ancient world. In ancient Egypt, quality was directly related to the ability to measure. All measuring instruments were "calibrated" to a standard. Due to lack of normal measuring units, the standard "cubit" was set by Pharaoh, which was a stick that matched the length of the Pharaoh's forearm (Ref 1). Every builder in the nation was required to have his standard cubit stick checked and calibrated. Failure to comply with this regulation would cost the builder's life.

Likewise, in the Roman Empire, quality was a life-and-death matter. If a building constructed by a Roman engineer was to collapse, and someone died, the engineer would be executed. Many of the aquifers and bridges built by those engineers are still standing. It is hard to believe that a bridge thousands of years old could still be used (Ref 2). Perhaps the explanation lies in the fact that, when the keystone that supported the bridge was laid, the engineer stood under the bridge. If the bridge collapsed, the engineer was the one to die.

In the early years of the last century, engineers were responsible for the manufacture and development of the early aircraft. Some people would not fly the plane unless the engineer accompanied them on their first flight. Things had not changed much from the Roman Empire era. The engineer's flying in the plane is similar to the engineer's standing under the bridge; the effect is the same, only the technology has changed.

In the last decades, many accepted definitions for the term "quality" had been set (Ref 2). For the engineering structures, quality can be divided into three major categories:

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- Quality of design (Ref 3)
- Quality of conformance to design (Ref 4)
- Quality of performance (Ref 5)

1.1 Quality of Design

The quality of design is concerned with the (a) specification of the in-service requirements of the structure and (b) clarification of the manufacturing processes and procedures. The cost of the product will increase when the in-service requirements of the structure increases or the specifications for the manufacturing processes (quality of design) increases. For example, the product will cost more when the tolerances decreases from ±10 μm to ±1 μm, or the safety factor increases from 1.3 to 1.6, etc.

1.2 Quality of Conformance to Design

The quality of conformance deals with whether the processes and procedures outlined in the design phase are being used and are effective. It monitors the conformance of material to specification and checks to ensure that tolerances are being held to the written specifications. This area is the one most often associated with quality control. The cost of the product can actually be decreased as the product quality increases by ensuring that the product conforms to the written specification. Failure to meet the design specifications implies rework to improve the quality of the product, or, if this is not possible, the final rejection of the product.

1.3 Quality of Performance

Quality of performance is the summation of design quality and quality of conformance. If either of the above is not adequate, then the quality of performance will not be adequate. Consider the case of a component that is designed to work under fatigue loads. If the cross section of the component is well calculated (designed), i.e., it can carry the service loads, but the surface roughness specifications are not met, then the component will probably fail early (poor quality of conformance to design). Likewise, if there is no specification for the maximum allowed surface roughness, then the component is susceptible to early failure (poor quality design).

In this paper, the issue of "quality" of cast aluminum alloys from various viewpoints is interpreted. There are many methods to characterize the quality of materials; the methods used currently for the quality evaluation of cast aluminum alloys, includes nondestructive testing, characterization of the microstructure and mechanical testing. With regard to mechanical testing, a number of quality indices have been devised to evaluate and characterize the quality of cast aluminum alloys. As these quality indices use different mechanical properties for the quality evaluation, they are expected to lead to different results. In this work, the application of proposed quality indices and their suitability is discussed for various situations, including minor variations in chemical composition, different solidification rate, solid solution, and artificial aging heat treatments.

2. Methods of Quality Evaluation in Cast Aluminum Alloys

In order for cast aluminum alloys to be used in engineering structures, quality evaluation should be applied. This involves (a) nondestructive testing, (b) microstructural characterization, and (c) mechanical testing of the component. Each of the above inspections/proofs gives different input for the alloy quality evaluation, while a combination of them all provides optimum quality evaluation. However, it is essential for the mechanical engineer who designs the mechanical parts of a structure to know the mechanical properties of the alloy. This enables the engineer to perform the stress analysis of the structure and the final structural design. For completeness, a quick description of the above categories is presented below.

2.1 Nondestructive Evaluation

Nondestructive evaluation includes methods that indicate the presence, and possibly the location and the size of a crack or an imperfection, without causing any destruction to the material. A serious drawback is that the evaluation of the results is strongly dependent on the human factor; the results are compared with standards. The commonly used methods in industry for quality evaluation of cast aluminum components are (a) liquid penetrant, (b) ultrasonics, and (c) radiography. Details about these inspection methods are found elsewhere (Ref 2, 6, 7).

Worth noting is a nondestructive quantitative methodology (Ref 8), developed to determine the mechanical properties of cast Al-7Si-Mg aircraft parts. This method is termed as the "etch penetrant inspection correlation (EPIC)." The system involves casting of plates along with test coupons and chemically milling the surface to reveal the true microporosity through dye-penetrant tests. The properties can be predicted by comparing the results of EPIC tests with standards. It is shown that there is a good agreement between EPIC system's values and properties determined from destructive testing.

2.2 Characterization of the Microstructure

It is well known that the mechanical properties of a cast component are determined by the cast melt conditions, such as the melt preparation and the casting process design (filling system) and by the casting parameters of the component (e.g., chemical composition, solidification rate, heat treatment). As for all metallic materials, the mechanical properties of the aluminum alloys are determined from their microstructure, which is the outcome of the above casting parameters. A number of research programs have been carried out to correlate the mechanical properties of the alloys with their microstructural characteristics. As different microstructural variables were found to influence the mechanical properties, different microstructural "quality" was defined. For completeness, a small description of these research efforts follows.

In the Boeing's research program Cast Aluminum Structures Technology (CAST) (Ref 9-11), the geometric characteristics of the aluminum cell and Si particles had been used to develop empirical, quantified expressions with all tensile properties such as yield strength, tensile strength, and elongation to fracture of the A357 cast alloy. Microstructural measurements such as the average particle size and area, aspect ratio, and spacing between particles had been used to evaluate the structural integrity of the material and to predict the above mechanical properties. Their work showed that the predictions had been compared well with the experimental results, and therefore this methodology could enable the producers to nondestructively measure and inspect the success of their efforts. It is a great benefit that this inspection can be made through easy-to-perform image analysis techniques.

The mechanical properties of a cast complex-geometry structure may vary due to differences in the solidification rate. Oswald and Misra (Ref 12) have used the dendrite arm spacing (DAS) to evaluate the tensile properties of Al-Si-Mg castings. It has been shown that variations of casting properties attributed to differences in the solidification rate can be evaluated by measuring the DAS and the tensile properties of an integral cast-on test bar. Predictive relationships that had been obtained between DAS and mechanical properties of the simple test bars were used to predict the properties in more complicated castings. Structure-property relationships can be very beneficial in determining the integrity of the casting and can be used as a tool for on-line quality control.

Likewise, Meyers (Ref 13, 14) developed empirical equations that predict the mechanical properties of the cast alloy A357 as a function of solid solution heat treatment time. The geometric characteristics of Si particles had been used to predict the ultimate strength and the elongation to fracture. For the unmodified A357 castings, the best microstructural predictors for both properties had been the size parameters, such as average area, mean diameter, and mean spacing of Si particles, while for the grain refined and modified castings, the numerical (areal, lineal, and interdendritic) densities of the eutectic Si-rich structures had provided the best estimates of both mechanical properties. Finally, a research summary on quantitative characterization of microstructures is available (Ref 15) to understand and distinguish the quantitative relationships of microstructure and mechanical properties.

2.3 Mechanical Testing

During the design phase of structural parts, certain requirements in mechanical properties arise that differ according to the in-service mechanical application. From the design point of view, the quality of an alloy is correlated to 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 material quality characterization. In aeronautical structure design, the fracture toughness of the material has to be taken into account; due to the very low safety factor of the whole structure, the scatter of the mechanical properties is also very important.

The recent advancements in understanding the background physical metallurgy of the age-hardened aluminum alloys (Ref 16-19), by the proper selection of chemical composition, solidification rate and heat treatment, allow the material's mechanical properties to be increased, according to the design office requirements. In addition, these advancements allow a better balance between tensile strength and ductility, i.e., "tailoring," within certain material dependent ranges. 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 of tailoring the alloy properties to a specific combination, etc. The above holistic view of evaluation and optimization of mechanical performance of cast aluminum alloys may be expressed through the proper involvement and interpretation of quality indices as they have been proposed (Ref 20-24) in chronological order of appearance in the published literature.

2.3.1 Quality Index Q (Drouzy et al.). In 1980, French researchers (Ref 20) 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:

$$Q = R_m + d \cdot \log_{10}(A_f) \qquad \text{(Eq 1)}$$

In conjunction with Eq 1, the probable yield strength R_p of an Al-Si-Mg alloy may be assessed by the equation:

$$R_p = a \cdot R_m - b \cdot \log_{10}(A_f) + c \qquad \text{(Eq 2)}$$

that takes into account the yield strength R_p of an Al-Si-Mg alloy (Ref 20). In Eq 1 and 2, a, b, c and d are alloy dependent, empirically determined coefficients. As referred in the literature (Ref 20), the quality index Q cannot be applied to assess the quality level of heat-treatable cast Al-7Si-Mg alloys at the over-aged condition. In a diagram of the ultimate tensile strength versus the logarithm of the elongation at fracture (schematically plotted in Fig. 1), Eq 1 and 2 represent sets of parallel lines called "iso-quality index" and "iso-yield strength" lines, respectively; they fit the experimentally obtained Q and R_p values resulting from minor variations in chemical composition, solidification conditions, and heat treatment of Al-Si-Mg alloys with a good approximation.

2.3.2 Quality Index Q_R (Din et al.). The exploitation of Eq 1 to other aluminum alloy systems than 3xx (Al-Si-Mg) has not been always manageable. Al-Cu alloys did not follow the behavior of Eq 1 and 2. The obtained results produced a kind of loop on the R_m versus A_f diagram (Ref 21), instead of a straight line, and therefore the quality index Q could not be exploited (Ref 21, 25, 26). In the same work (Ref 21), the available experimental results were fitted by introducing the expression:

$$Q_R = R_p + m \cdot A_f \qquad \text{(Eq 3)}$$

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 Eq 3 is applied to the Al-Si-Mg alloys, m takes the value of 50.

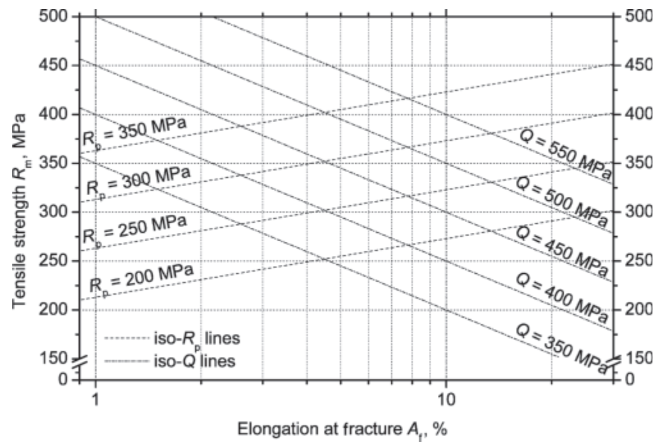

Fig. 1 Quality map for the Al-7Si-Mg aluminum alloys suggested by Drouzy et al. on the basis of iso-Q lines of Eq 1 and iso-R_p lines of Eq 2

2.3.3 Quality Index Q_C (Caceres). The quality index Q lacked a proper theoretical grounding. The physical basis of Eq 1 has been studied by Caceres (Ref 22), who used the work hardening characteristics of the Al-7Si-Mg alloys to estimate the elongation at fracture A_f of a specimen if it did not have any structural defects. Supported by the minimal necking formation of these alloys, A_f was taken to be equal to maximum uniform elongation, because fracture occurs when engineering stress reaches the tensile strength R_m. Caceres defined a new relative ductility parameter:

$$q = \frac{A_f}{A_{fc}} \cong \frac{A_f}{n} \qquad \text{(Eq 4)}$$

where A_f is the elongation at fracture of the current specimen and A_{fc} the elongation at fracture of the "ideal"/defect-free specimen of the same alloy. Caceres calculated the A_{fc} by using the strain-hardening exponent n in the power-law relationship:

$$\sigma' = H \cdot \varepsilon'^{n} \qquad \text{(Eq 5)}$$

where σ' is the true stress, H is the alloy's strength coefficient, and ε' is the true strain. Ignoring the difference between true and nominal strain, the nominal stress-strain curve was approximated by:

$$\sigma \cong H \cdot \varepsilon^{n} \cdot e^{-\varepsilon} \qquad \text{(Eq 6)}$$

where σ and ε are the engineering values of stress and strain, respectively. Eq 6 can be used to generate tensile flow curves using various values of H and n, as shown in Fig. 2. Curves representing contours of constant relative ductility, or iso-q curves, can be described in terms of the engineering stress and strain by combining Eq 4 and 6:

$$\sigma = H \cdot \varepsilon^{\varepsilon/q} \cdot e^{-\varepsilon} \qquad \text{(Eq 7)}$$

The iso-q curves obtained above were plotted and are found schematically in Fig. 2. In a series of papers (Ref 27-29), an analytical model has been presented, where the quality index was related to the necking onset strain of the material using

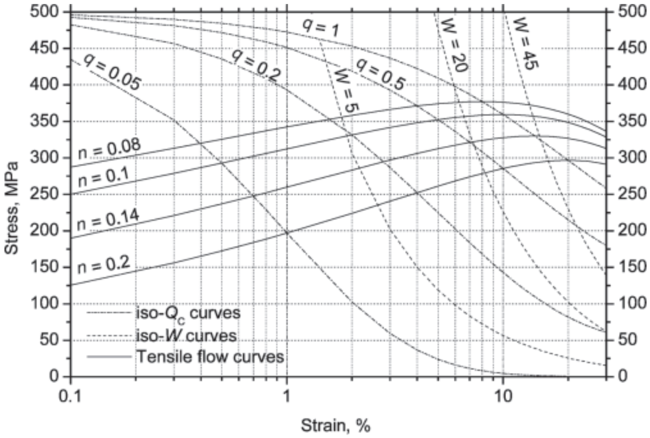

Fig. 2 Quality map for aluminum alloys suggested by Caceres on the basis of (a) calculated flow curves of Eq 6 with constant $H = 500$ MPa and various n values; (b) iso-q lines of relative ductility plotted with Eq 7 and constant $H = 500$ MPa; and (c) iso-W curves of constant energy absorption plotted with Eq 15

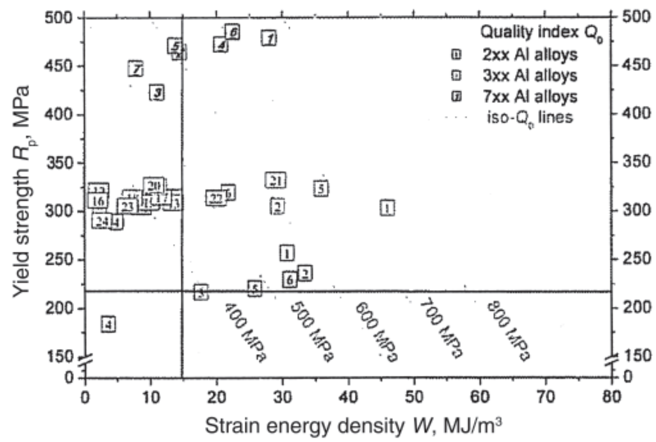

Fig. 3 Quality map of cast aluminum alloys suggested on the basis of the index Q_0 of Eq 10 (graph taken from Ref 33 and numbers refer to different alloys). The solid lines are the property design prerequisites of cast aluminum alloys for aeronautical applications.

continuum mechanics. The quality index Q_C finally became a function of the material's yield strength R_p:

$$Q_C = R_m + 0.4 \cdot R_p \cdot \left(\frac{E}{a \cdot R_p}\right)^n \cdot \log_{10}(A_f) \quad \text{(Eq 8)}$$

where E is the Young's modulus, and a is a scale factor of order 1.

2.3.4 Quality Index Q_D (Alexopoulos and Pantelakis). For the case of the index Q_D (Ref 23), the quality had been interpreted as the potential of the alloy for mechanical performance. This evaluation had been the outcome of the balance between the material properties strength and ductility. The material properties that had been used in Q_D were yield strength R_p and strain energy density W; they were selected such as to fit the aeronautic design properties prerequisites. Yield strength accounted for the strength and set the region of allowable service stresses of the component. This is actually the main customer requirement of a structural component. Strain energy density accounted for the tensile ductility, as it characterizes the energy required for material fracture. Strain energy density is another customer requirement of a structural component, as high energy to fracture implies freedom from deficiencies, and therefore high "quality." Strain energy density had been also directly related to fracture toughness (Ref 30). Hence, the quality index Q_D involved also information about the material failure through yielding or fracture and could give a direct indication for the suitability of a cast aluminum alloy for use in damage tolerance applications. The index was determined as:

$$Q_D = K_D \cdot Q_0 \quad \text{(Eq 9)}$$

where Q_0 characterizes the tensile performance of a material and K_D stands for a dimensionless factor that characterizes the scatter in tensile properties of the evaluated material. The quantity Q_0 was formulated as:

$$Q_0 = R_p + 10 \cdot W \quad \text{(Eq 10)}$$

Strain energy density W may be evaluated from the area below the true stress-true strain tensile curve as:

$$W = \frac{dU}{dV} = \int_0^A \sigma \cdot d\varepsilon \quad \text{(Eq 11)}$$

where U is the strain energy, V the material volume, and A the tensile elongation to fracture. In Eq 10, strain energy density W is multiplied by the empirical factor 10. The value 10 represents a typical value of the ratio R_p/W for property optimized advanced aluminum alloys, which are currently used in aircraft applications (e.g., aluminum alloys 6013, 2091, and 8090) (Ref 31). The factor K_D in Eq 9 was defined as:

$$K_D = \left(\frac{R_{pi}}{R_{pmax}} + \frac{W_i}{W_{max}}\right) \quad \text{(Eq 12)}$$

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 the k investigated specimens, respectively. For a specific alloy batch, K_D characterized the scatter in the properties R_p and W by evaluating the different specimens. The first term of Eq 12 reflects the variations in flow velocity and direction in the quench tank and/or the temperature variations in the aging furnace. The second term is kind of a Weibull modulus, which had been used in (Ref 32) to characterize the reliability of cast aluminum alloys by means of lack of structural defects.

The average quality index of an alloy modification is given by:

$$Q_D = \frac{\sum_{i=1}^{k} Q_{Di}}{k} \quad \text{(Eq 13)}$$

An example of the quality index Q_D can be found in Fig. 3, where a quality map is presented. In the specific example the scatter of the mechanical properties had been neglected; the alloys were evaluated by means of their average mechanical properties. Iso-Q_0 lines of Eq 10 are plotted in Fig. 3 to distinguish the high-quality materials. The solid lines in the same figure represent property barriers, set by the aeronautical cast

Table 1 Material input for the calculation of proposed quality indices and possible applications in cast aluminum alloys

Application	Quality index				
	Q	Q_R	Q_C	Q_D	Q_E
Material's mechanical properties used to calculate the quality index	R_m, A_f	R_p, A_f	E, R_p, R_m, A_f	R_p, W, and scatter	W
Comparison between alloys from different alloy series	No	No	Yes	Yes	No
Comparison between alloys from the same alloy series with minor variations in chemical composition	Only in 3xx	Only in 2xx and 3xx	Yes	Yes	Yes
Comparison between alloys with different solidification rate	Only in 3xx	Only in 2xx and 3xx	Yes	Yes	Yes
Comparison between alloys with different solid solution heat treatment	Only in 3xx	Only in 2xx and 3xx	Yes	Yes	Yes
Comparison between alloys with different artificial aging heat treatment	Only in 3xx	Only in 2xx and 3xx	Yes	Yes	No
Material property domination on the quality index	Strength (R_m)	Ductility (A_f)	Balanced	Balanced	Ductility (W)

components manufacturers (Ref 34, 35) in order that a cast aluminum alloy could be used in a aeronautical component.

2.3.5 Quality index Q_E (Tiryakioglou et al.). Tiryakioglou et al. (Ref 24) 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:

$$Q_E = \frac{W}{W_c} \qquad \text{(Eq 14)}$$

W is the strain energy density of the material and is expressed by Eq 11, and W_c is a fixed value of strain energy density of the "ideal" alloy modification with no structural discontinuities. Q_E takes values less than 1 and larger than 1. If there are structural discontinuities in the specimen, Q_E will be less than 1, which indicates how far the current structural integrity is from the target (defined as equal to 1). If there are no structural discontinuities in the specimen, it will absorb energy more than W_c, which will yield a number greater than 1. The authors of this work (Ref 24) suggest that this is meaningless because the point is to reach the target value of "ideal" property W_c. This methodology has been applied in cast aluminum alloys Al-Si7-Mg with varying Mg content.

3. Discussion of the Quality Indices and Their Possible Applications

The quality index Q had been the pioneer of the so-called "quality indices." The methodology proposed in (Ref 20) provided a very useful tool to reduce the experimental effort for developing or optimizing cast Al-7Si-Mg alloys. The quality index Q has been widely accepted because of its simplicity and has been used in a variety of situations, e.g., to assess the effects of slight variations in chemical composition of A357 alloy (Ref 20, 26), and the effects of all applicable heat treatments (Ref 20, 34, 36). A synopsis of the uses of Q for aluminum alloy quality evaluation can be found in Table 1. Involvement of Q for the quality evaluation of different artificial aging heat treatment conditions of A357 alloys leads to very realistic results (Ref 35) and indicates that the dependency of the quality index Q on the aging time is similar to the dependency of the tensile strength R_m to the aging time. This has been justified for all possible applicable artificial heat treatment conditions, including under-aging and peak aging conditions. A negative aspect of the index Q is that it works in above heat treatments and not to some other, such as the over-aging condition. As followed by the observations made in (Ref 37), index Q is more sensitive to tensile strength than to tensile ductility variation.

The exploitation of Q for the quality evaluation of alloy systems other than Al-Si-Mg (3xx) has not been always manageable. Experimental results from Al-Si-Cu-Ni-Mg alloys, used in pistons of internal combustion engines (Ref 38), showed, in general, a similar mechanical behavior to the Al-7Si-Mg alloys and therefore, the quality index Q can be exploited. The coefficient d in Eq 1 was set equal to 190 MPa. The application of Q to evaluate cast aluminum alloys from other series than 3xx resulted in poor success (Ref 23, 37), and this makes the direct comparison of aluminum alloys from different series not feasible. Experimental results from Al-Cu alloys in (Ref 21) could not be evaluated by means of index Q, and a modified quality index Q_R, had been proposed in the same work. Index Q_R uses the yield strength of the material, instead of the tensile strength. The coefficient m in Eq 3 takes different values for 2xx and 3xx aluminum alloy series. This makes the comparison of aluminum alloys from different series impossible. It should be noted that the direct comparison of cast aluminum alloys from different series refer only to compare their tensile mechanical properties to be used in engineering structures. Index Q_R can be used to evaluate the effect of minor variations in chemical composition of 2xx and 3xx cast alloys, and to assess the effect of all applicable heat treatment conditions on quality evaluation of the above aluminum alloys. Comparison of the dependencies of the quality index Q_R and the elongation to fracture on the aging time of A357 alloys (Ref 35), confirms the strong sensitivity of Q_R on variations of the tensile ductility. Use of Q_R is expected to lead to reasonable results in engineering applications where the variations in tensile ductility are considered to be the essential parameter for alloy quality evaluation.

Caceres related the iso-Q and iso-R_p lines of Eq 1 and 2 to the material's plasticity (Ref 22). The evaluation of the alloys can be made through quality index charts. The quality index charts have been extended to include information about the energy absorption when the alloys are deformed up to fracture. The strain energy density (energy absorption) had been calculated as a function of R_m and A_f by integrating the tensile flow curve with various assumptions made in (Ref 39) as:

$$W = \int_0^{A_f} \sigma \cdot d\varepsilon = \frac{R_m \cdot A_f \cdot e^{A_f}}{n+1} \cong 0.8 \cdot R_m \cdot A_f \cdot e^{A_f} \quad \text{(Eq 15)}$$

The quality index chart enables the comparison between aluminum alloys from different series or from the same series with minor variations in chemical composition (Ref 28, 29). The methodology has been successfully applied to assess the effects of heat treatment conditions on various cast aluminum alloys (e.g., Ref 22, 25). The evaluation of the alloys when using quality index Q_C, results to very realistic ranking. Experimental results and quality evaluation (Ref 25, 28, 29) suggests that Q_C is a balanced index, without being strongly influenced by either strength or ductility.

Quality index Q_D uses the material's yield strength and strain energy density (tensile toughness) for quality evaluation. The indices Q, Q_R, and Q_C do not take as an input the toughness of the alloy for the quality evaluation. It is well known that elongation to fracture is analogous with strain energy density, and thus implying that it can be taken into account. The scatter in mechanical properties can be taken into account when using the Q_D, while none of the above quality indices account for the scatter for the quality evaluation of the alloy. Quality evaluation of cast aluminum alloys from different series had been made with realistic results (Ref 23). Index Q_D can be used to evaluate the effect of minor variations in chemical composition of cast alloys (Ref 37), and because it had been successfully applied to evaluate the effects of artificial aging heat treatment conditions on the cast aluminum alloy A357 (e.g., Ref 35), it can be also used to assess the quality of various artificially aged cast aluminum alloys. Note that a specific work (Ref 33) has already addressed the effects of all of the above parameters to quality indices of various cast aluminum alloys by means of generated quality maps. Although Q_D gives realistic results in all the above cases, the empirical coefficient 10 in Eq 10 slightly favors high-toughness alloys than high-strength alloys. Materials with high toughness values expressed in the present evaluation through the strain energy density W are desired in damage tolerance applications. According to (Ref 30), strain energy density may be directly related to the material fracture toughness through the equation:

$$W = \frac{(1+\nu)(1-2\cdot\nu)\cdot K_{Ic}^2}{2\cdot\pi\cdot E\cdot r_c} \quad \text{(Eq 16)}$$

In Eq 16, K_{Ic} stands for the plane strain critical fracture toughness of the material, E and ν are the material's modulus of elasticity and Poisson's ratio, respectively, and r_c is a material constant.

As the quality index Q_D involves the strain energy density W, it can be evaluated only if the tensile flow curve of the alloy is known, thus making difficult the use of Q_D for assessing a large number of alloy variations. Also the comparison of existing cast aluminum alloys on the basis of Q_D values is not always a straightforward procedure as, in many cases, the available material databases involve tensile properties, such as tensile strength R_m, yield strength R_p, and elongation to fracture A_f, but not the strain energy density W or the tensile flow curve for evaluating W. To overcome this, W had been calculated as the integral of the tensile flow curve, and expressed as a function of R_m and A_f (Ref 40). Using the quality index Q_D and by neglecting in the quality evaluation of an alloy the scatter in mechanical properties, i.e., by assuming $K_D = 1$ in Eq 9, the quality level of an alloy is characterized by the quantity $Q_0 = R_p + 10 \cdot W$; it includes mean values of the material properties yield strength and strain energy density. When substituting the strain energy density, the quality index Q_0 can be calculated as:

$$Q_0 = R_p + \frac{10\cdot R_m\cdot \ln(1+A_f)\cdot(1+A_f)}{\ln(1+A_f)+1} \quad \text{(Eq 17)}$$

Eq 17 facilitates the widespread use of the quality index Q_D, because the quality level of the alloys can be calculated by the available material databases.

To further facilitate the exploitation of Q_D for quality assessment in fast, production lines, an approximate expression had been proposed for the quality assessment of Al-Si-Mg alloys (Ref 40). This approximation allows for calculating the alloy quality by using hardness and Charpy impact test values. Based on the performed experiments, empirical correlations between yield strength R_p and Rockwell E hardness as well as between impact resistance R_{CVN} and tensile strain energy values W were derived such that hardness and impact energy values respectively, may substitute the contribution of tensile strength and ductility in the initial equation of the quality index Q_D. By neglecting the scatter of the mechanical properties, the quality index Q_0 that characterizes the material's tensile mechanical performance was approximated as Q_{0HI} that characterizes the material's ability to withstand to full compression plasticity stress (Rockwell hardness) and simultaneously to absorb energy during crack growth at high (impact) velocities. The equation of calculating Q_{0HI} has been defined as:

$$Q_{0HI} = h\cdot \mathrm{HRE} + p\cdot R_{CVN} - y \quad \text{(Eq 18)}$$

where h, p, and y are empirical, material-dependent coefficients. Note that steel manufacturers, to compare their products, currently use the same mechanical properties. The equation used to define the technological value (quality) of a austenitic steel in terms of strength/toughness combinations, is:

$$K = \frac{W_{CVN}}{1356\cdot(HRC-35)^3} \quad \text{(Eq 19)}$$

where W_{CVN} is the Charpy impact energy [in J] and HRC [no units] is the Rockwell hardness in C scale. Similar expression applicable for evaluating the quality of cast aluminum alloys are not known to the author. An example of the quality evaluation by means of tensile testing and measuring hardness and impact values can be seen in Fig. 4 for different artificial aging heat treating times. The average error in calculating the quality by Eq 10 and 18 is about 7.5%. With regard to the usual scatter in the mechanical properties of cast aluminum alloys the expected error when estimating Q_D by means of the proposed approximations is acceptable. On the other hand, the reduction in time, effort, material, and cost for producing the data required for estimating Q_D is appreciable. For the case of precision aluminum castings, which are usually involved in aircraft structural applications, this benefit increases further as the tensile specimens have to be produced in most cases by precision casting as well, e.g., (Ref 34).

The quality index Q_E had been devised to assess the effects of minor variations in chemical composition on the structural integrity of Al-7Si-Mg alloy (Ref 24). Index Q_E uses only the strain energy density W of the alloy under evaluation and ig-

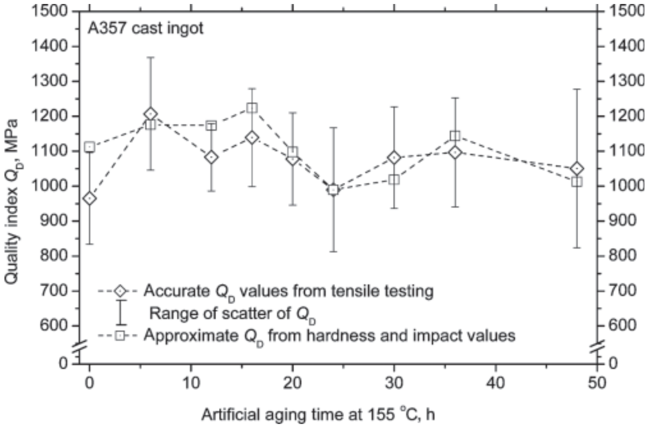

Fig. 4 Example of quality calculation of the index Q_D of Eq 13 by means of hardness and impact testing for cast alloy A357 and exploiting Eq 18 (data from Ref 40)

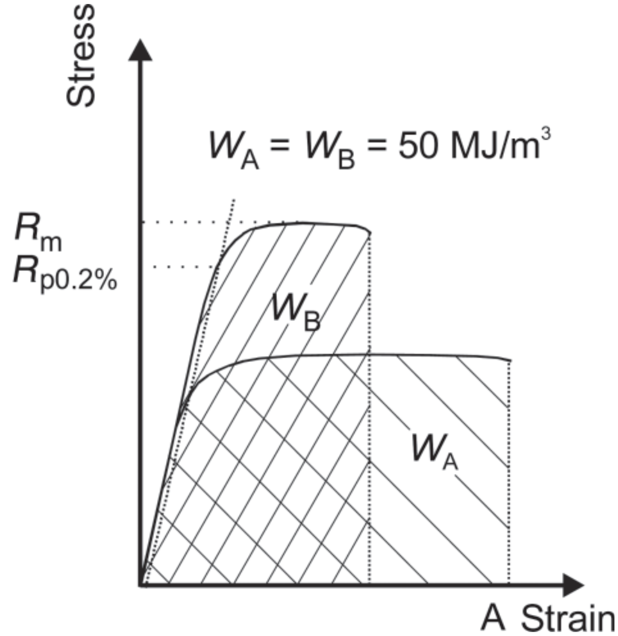

Fig. 5 Example of tensile flow curves of two cast aluminum alloys having the same strain energy density W values

nores the strength level of the alloy (Table 1). The dependence of Q_E on strain energy density may favor high ductility materials, as they have the ability to absorb more energy (toughness). It is the author's opinion that Q_E can be only used to evaluate the effects of minor variations in chemical composition, of different solidification rate and solid solution heat treatments. It is well known (Ref 17-19) that the age-hardened aluminum alloys, by the proper selection of artificial aging heat treatment conditions, allows balance of tensile strength against ductility within certain material dependent ranges. The use of Q_E to compare alloys with different artificial aging heat treatment conditions may lead to wrong results. To locate a possible misjudgment, the following example can be made. Suppose there are two different artificial heat treatment conditions, A and B, of the same age-hardened aluminum alloy. The tensile flow curves of the two alloys can be seen schematically in Fig. 5. Suppose both alloys have the same strain energy density value, which is also equal to the targeted value, e.g., $W_c = W_A = W_B = 50$ MJ/m^3. Both alloys have optimized quality according to Q_E index ($Q_E = 1$), and therefore the same ability to absorb energy. This is essential for material selection in damage tolerance applications. However this is not enough, because the design engineer would select an aluminum alloy of the highest damage tolerance ability and with the higher yield strength to avoid plastic yielding. Furthermore, it is the author's opinion that the direct comparison between alloys from different alloy series cannot be made by means of the Q_E index. The authors suggest that a different W_c value shall be set for a different alloy. Then, different values of W_c shall be also set to evaluate the quality from another aluminum alloy series, e.g., 2xx or 7xx. If the same W_c value will be set for all major alloy series, this will conclude to one of the following results: (a) low value of W_c and therefore the majority of aluminum alloys have optimized quality, and (b) medium-to-high value of W_c that will lead to picture the 2xx and 3xx alloys as optimized quality alloys, because they have the highest possible ductility properties. Application of the index Q_E in terms of producing or developing a specific cast aluminum alloy may lead to very realistic results.

4. Conclusions

- An investigation on the term "quality" used in engineering structures and cast aluminum alloys is made. The quality evaluation of cast aluminum components can be made through nondestructive inspection, microstructural examination and mechanical testing.
- From the design point of view, the "quality" of an alloy is correlated to the required mechanical performance for the safe operation of the structural part. This evaluation for the cast aluminum alloys can be made through quality indices.
- As quality indices use different mechanical properties to evaluate "quality," different results are obtained. Possible applications of proposed quality indices have been discussed, including variations in chemical composition, different solidification rate, solid solution, and artificial aging heat treatments.

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