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Influences of alloying elements, solution treatment time and quenching media on quality indices of 413-type Al–Si casting alloys

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Abstract

Quality charts were generated using four models of quality indices in order to evaluate the mechanical properties and quality of T4-treated 413-type Al–Si casting alloys. The purpose of this study is to investigate the influence of a number of parameters on the mechanical properties and quality of 413-type alloys. These parameters are the addition of the alloying elements Sr, Mg, Cu, Ag, Zn, La, Ce and Ni; the solution heat-treating time for periods of 4 and 24 h; and two quenching media: ambient air and hot water. Analysis of the quality maps generated shows that the alloying elements have a considerable influence on mechanical properties but only a slight influence on alloy quality. It was observed that solution heat-treating for a period of 24 h does not have any significant effect on material strength although some positive influences may be observed on ductility and quality of the alloys under investigation as compared to the 4 h-duration. Using hot water (60 °C) as a quenching medium improves both the strength and the quality of these alloys. Quality indices and quality charts are useful tools for engineering applications with a view to facilitating the selection of the most suitable processing conditions and to obtain the best compromise between quality and mechanical properties of the alloys investigated. Making use of quality charts will contribute to the selection of the most appropriate alloys for a particular application in accordance with service conditions in real life.

Keywords: Quality charts; Quality indices; Alloying elements; Intermetallic phases; Quenching media; Solutionzing time; Mechanical properties; 413-type Al–Si castings

1. Introduction

Aluminum–silicon casting alloys have numerous applications in the automotive industry because of a specific feature involving high strength-to-weight ratio, thereby increasing mechanical performance and decreasing fuel consumption. The 413.0-type Al–Si casting alloys are characterized by their superior casting characteristics and low shrinkage resulting from their high silicon content (11–13 wt.%). This high silicon-content, however, may cause machining difficulties. These castings are used when high corrosion resistance, low density and pressure tightness are desired [1–4]. Improvements in the mechanical performance of such alloy castings may be carried out through the addition of suitable alloying elements and adequate heat treatment procedures.

Alloying elements are added to Al–Si casting alloys to improve the mechanical properties of such castings. *Strontium* (Sr), known as a chemical modifier, is added to Al–Si casting alloys to change the coarse, acicular eutectic silicon to a fine, rounded form which improves alloy ductility and strength [5,6]. *Magnesium* (Mg) and *copper* (Cu) are two essential alloying elements commonly added to Al–Si castings to increase their strength, although this improvement occurs at the expense of ductility [7–10]. *Silver* (Ag) has limited applications in certain aluminum–copper premium-strength alloys for improving corrosion resistance; it also contributes to the precipitation hardening of such alloys [2,4]. *Zinc* (Zn) provides no significant benefits in aluminum castings, however, the addition of this element with magnesium and/or copper results in naturally-aging compositions [2,4]. *Nickel* (Ni) is commonly used with copper to improve the mechanical properties at elevated temperatures [2,4,8]. *Rare earth metals* such as *lanthanum* (La) and *cerium* (Ce) have been found to improve the mechanical properties of Al–Si castings where they modify the

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microstructure and enhance the tensile strength and ductility [11–14].

Heat treatment in aluminum castings which contain other alloying elements, especially copper and magnesium, are of critical importance in obtaining the best combination of strength and ductility [10,15]. Heat treatment of aluminum alloys consists of three stages: (i) *solutionizing* to dissolve the soluble phases; (ii) *quenching* to retain the supersaturated structure obtained from the first step; and (iii) *aging* where the precipitation of solute atoms occurs either at room temperature (*natural aging*) or at higher temperature (*artificial aging* or *precipitation heat treatment*) [10,16–18]. In certain cases, the heat treatment tempers consists only of solution heat treatment and quenching in which case it is referred to as a T4-temper.

The quality of aluminum casting alloys is considered to be one of the most critical factors controlling the selection of an alloy casting for a specific application. The alloy quality in engineering applications refers to reaching a suitable compromise drawn from among numerous factors which would produce minimum risk and maximum performance in conjunction with economical efficiency. Alloy composition, solidification rate, heat treatment procedures, casting defects (such as porosity, and/or inclusions), and such microstructural features as grain size, and intermetallic phases, are all parameters which influence the alloy quality since they affect the mechanical properties of the castings.

The quality of aluminum alloy castings may be defined using numerical values correlated to their mechanical properties. Drouzy et al. [19] first proposed these numerical values called quality indices in 1980; they investigated the influence of solidification conditions, alloy composition, and heat treatment procedures on the mechanical properties of alloys 356 and 357. The first quality index proposed by Drouzy et al. may be represented by:

$$Q = \sigma_{\text{uts}} + k \log(E_{\text{f}}) \tag{1}$$

where Q is the quality index in MPa; σ_{uts} refers to the ultimate tensile strength in MPa; E_{f} refers to the elongation to fracture in pct; and k is a material constant.

The concept expressed in Eq. (1) has the drawback of lacking the proper theoretical background or physical meaning which was covered by Cáceres and co-workers [20–24]. Cáceres defined a relative quality index $q = E_{\text{f}}/E^*$ which expresses the ratio of the engineering strain at failure (E_{f}) and the engineering strain at the onset of necking (E^*); accordingly, the samples which fracture before the onset of necking will be of a lesser quality than those which fracture at or beyond the onset of necking. The relative quality index, q, may be expressed in terms of the engineering stress and strain by the relation:

$$\sigma = KE^{E/q}\text{e}^{-E} \tag{2}$$

where σ and E are the nominal stress and strain, and K is the material strength coefficient. Eq. (2) was used to generate the *iso-q* lines in the quality charts where the line $q = 1$ represents the maximum quality, since it provides the best ductility for such samples when the sample reaches the necking point. When $q < 1$, it represents fewer quality samples since such samples provide lower ductility or fracture before necking. Eq. (2) however does not calculate the Q_{C}-values, which are determined using Eq. (2.1):

$$Q_{\text{C}} \approx K[1.12 + 0.22\ \ln(q)]$$
$$\text{where}\quad Q_{\max}\quad \text{is obtained at}\ q = 1 \tag{2.1}$$

Din et al. [25] concluded that the quality concept proposed by Drouzy et al. in Eq. (1) is not transferable to the Al–Cu alloy system. Accordingly, a modified definition of quality index was proposed as follows:

$$Q_{\text{N}} = \sigma_{\text{ys}} + \text{d}E_{\text{f}} \tag{3}$$

where σ_{ys} is the yield strength; E_{f} is the elongation to fracture; and d is a material constant which has the values of 7.5 for A206, 13 for A201, and a value of approximately 50 for alloys A356 and A357.

Tiryakioglu et al. [26] proposed a quality index based on the concept that energy absorbed is directly related to the effective crack length produced by a discontinuity where Q_{E} represents the fraction of the target energy or toughness that is absorbed by the specimen. The new index may be calculated by comparing the toughness of the specimen W with its threshold toughness W_{C} the toughness of the discontinuity-free sample which is presented by:

$$Q_{\text{E}} = \frac{W}{W_{\text{C}}} \tag{4}$$

Quality index as expressed in Eq. (4) is not recommended, however, since it does not include material strength as a parameter which controls alloy quality together with material toughness. In general, the selection of a casting for a certain application requires obtaining the best compromise between mechanical properties and alloy quality; thus, toughness alone is insufficient for selecting a specific alloy for a given application.

Alexopoulos and Panelakis [27] introduced a new quality index Q_{D} to describe prerequisite features in aluminum casting alloys for aeronautical design. This new quality index Q_{D} takes into account the balance between material strength, ductility, and the scatter of mechanical properties, as follows.

$$Q_{\text{D}} = K_{\text{D}}Q_0 \quad \text{with} \quad Q_0 = \sigma_{\text{ys}} + 10W \tag{5}$$

where K_{D} is a dimensionless factor that characterizes the scatter in mechanical properties, Q_0 characterizes the average mechanical properties of the material, and W refers to the strain energy density (energy per unit volume).

Based on the proposed quality indices mentioned above, the generating of quality charts is an engineering objective. These charts provide a simple tool for selecting the best compromise between mechanical properties and the quality of the materials to be used in industrial applications. Furthermore, these quality maps may be used to select the most favorable processing conditions for castings so as to obtain the highest quality and the best mechanical properties possible, including alternative heat treatment procedures, the addition of alloying elements, and changes in solidification conditions. It should be noted that the qual-