A REVIEW OF THE PHYSICAL METALLURGY OF 6013

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Abstract

This paper reviews the basic physical metallurgy of 6013. The emphasis is on composition, typical phases present and their influence on properties.

Introduction

During the 60's and 70's aluminum alloy development for structural materials flourished. Modifications to the compositions of established alloys resulted in significant improvements in properties such as strength, fracture toughness and fatigue crack growth resistance. However, by the mid 1970's the focus on properties expanded to include density. The emergence of density as an important factor governing the selection of alloys forced alloy developers to concentrate on metal-matrix composites, non-traditional alloy additions such as lithium added to aluminum, and alternative processing methods such as rapid solidification. This research resulted in numerous new monolithic and composite materials.

Economic, environmental and global competition are forcing U.S. industries to produce materials not only with the required properties, but also in a more cost-effective manner than in the past. Alloy development now focuses on optimizing composition and processing to produce improved alloys at less cost and with less waste. This approach requires that attention be paid to existing commercial alloys, incorporating the effects of all the processing steps including casting, preheating, hot and cold working and precipitation heat treating as well as composition.

Recent research has focused on the 6XXX series alloys. These alloys are heat-treatable aluminum alloys that find their greatest use in applications requiring medium to high strength, excellent formability and good corrosion resistance. The combination of these properties makes them potentially more desirable for certain applications than the stronger 7XXX alloys. The importance of the alloys in this series can be realized by considering the fact that alloys 6061 and 6063 are among the largest selling heat-treatable alloys in the United States [1]. The alloy 6013, introduced in 1983, develops improved mechanical properties over its 6XXX series predecessors; and hence, it may outperform other 6XXX alloys in many applications [1,2]. 6013 may also be suitable for applications which traditionally utilize aluminum alloys from other series. For example, 6013 has a combination of toughness and tensile strength comparable to that of 2024. It develops tear strength between those of 2024 and 7475, both of which are extensively used in aerospace applications. 6013-T6 sheet was selected to replace the traditional 2024-T3 clad sheet on the U.S. Navy's P-7A plane because this replacement would reduce the manufacturing costs for formed parts and lead to improved mechanical properties such as fatigue strength and fracture toughness [3].

In order to produce an alloy that might be useable in aerospace and automotive applications, control of the degree of recrystallization and the recrystallized grain size, when recrystallization occurs, are necessary [4]. The emphasis of our research [6-10] has been quantifying changes in microstructure that occur due to modifications to alloy composition, casting, preheating, hot working and solution heat treating steps. This step is necessary because before predictive models that relate the microstructural evolution with processing variables can be developed, quantitative microstructural investigations on the influence of composition and processing are necessary. The results of our microstructural investigations will be summarized and specific factors that have the greatest potential for controlling microstructure will be presented in a subsequent paper [11].

The steps involved in the processing of a heat-treatable aluminum alloy include: (1) casting, (2) preheating, (3) hot working, (4) solution heat treating (during which recrystallization may occur), (5) quenching and (6) aging. All the steps are critical and equally important since the microstructure that develops during each step depends on the processing parameters of that step and the microstructure which existed at the end of the previous step.

Since compositional variants of 6013 are of potential interest, it is useful to discuss the roles of each element in alloy 6013. Figure 1 shows the acceptable ranges for the elemental composition of alloys in the 6XXX series. Not all elements in 6013 can be varied, and in the following section, a short discussion is presented regarding the alloying elements present in 6013 along with their role.

Magnesium and Silicon

Magnesium and silicon are often added in balance to form the quasi-binary Al-Mg_2Si with a proper ratio for Mg_2Si as Mg/Si = 1.73 by weight [5]. The distribution of Mg_2Si precipitates in an age-hardened alloy is one of the main factors that controls mechanical properties of the 6XXX series alloys. Most alloys in this series have either magnesium or silicon in excess. An excess in magnesium leads to improved corrosion resistance but reduces strength and formability. An excess in silicon leads to higher strength and ductility without loss of formability and weldability. However, 6XXX series alloys with excess silicon are susceptible to intergranular corrosion since silicon tends to precipitate on grain boundaries [5]. For 6013, it is preferred to have silicon in excess of the theoretical estimated value [1]. The extent of the excess, however, must be relatively small to combine high yield and tensile strengths with improved toughness and impact resistance.

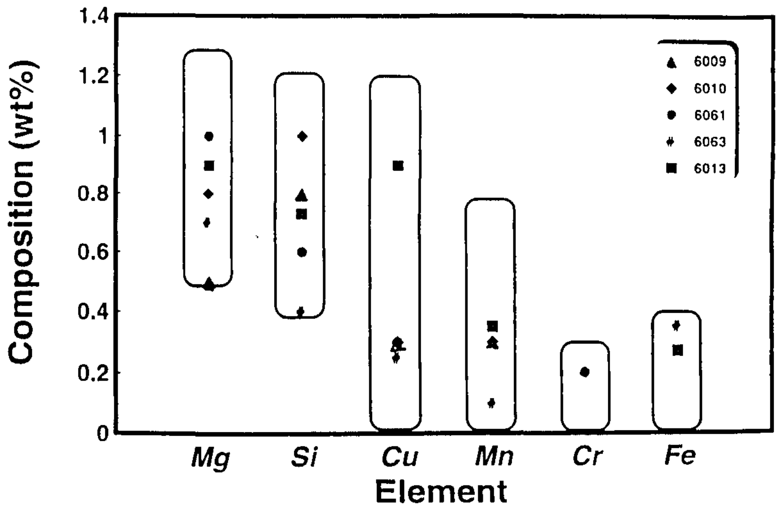

Figure 1 Nominal composition ranges of alloying elements and impurities in typical 6XXX series alloys.

<u>Copper</u>

Copper is often added to Al-Mg-Si alloys in the range of about 0.25% to 1.0% to modify the metastable precursor to Mg_2Si. Copper additions provide a substantial strength increase, but, at the same time, impair corrosion resistance [1,5]. Preliminary investigations [1] indicated that when copper exceeds 0.9%, 6013 becomes more prone to corrosion problems. For instance, increasing copper from 0.9 to 1.4% can increase general corrosion damage (measured by strength loss) by as much as 45% to 80% [1]. These increased copper levels also lead to the formation of an intermetallic $Al_4CuMg_5Si_4$, the so-called Q-phase. This phase has a rod-like shape and is formed by a solid state transformation as the solidified ingot cools. Depending on alloy composition, Q-phase may dissolve and reprecipitate during various stages of processing. The microstructures that can contain the Q-phase include: (a) the as-cast microstructure, (b) the as-heated microstructure prior to hot deformation and (c) the microstructure after precipitation hardening.

Q-phase precipitates in an as-cast microstructure are coarse (approximately 2-4 microns in length) and have shown to be detrimental to fracture toughness and corrosion performance of the alloy [1]. By control of composition and thermal processing, however, the preheated ingot can be made substantially free of this phase [1]. Q-phase precipitates that form during heating prior to hot working are finer and more uniformly distributed than those in the as-cast state [6]. However, the presence of this phase in the microstructure prior to the deformation may have a pronounced effect on the microstructural development during hot deformation [6]. Q-phase precipitates, or a quaternary Al-Cu-Mg-Si precursor, that form during artificial aging treatment are fine and provide a major contribution to strength in 6013. Along with Mg_2Si and possibly θ', the presence of quaternary phase precipitates helps 6013 to develop higher strength than 6061-T6.

Manganese

Typically, manganese is present from a minimum of about 0.10% to a maximum of about 1.0%. A range of 0.25% to 0.60% is preferred to optimize strength [1]. In 6013, manganese participates in the formation of two different types of phases: one type forms by a liquid → solid transformation and the other type by a solid → solid transformation. Those that form from the liquid are coarse and are referred to as the so-called *Chinese script* [5], whereas the phases that form by solid state transformations are called dispersoids and are small with sizes ranging from 0.1-0.3 microns [7]. The effects of the dispersoids on the recrystallization kinetics of 6013 are of major interest since these particles play an important role in retarding boundary movement during recrystallization anneal. There are two crystallographic forms of the Mn-bearing dispersoids depending on the local iron content. When the local iron content is low, the simple cubic phase α(AlMnSi) having Laue group PM3, forms, but when the local iron content is sufficiently high, the body-centered phase α(AlFeMnSi) forms [8].

Iron

Iron is the main impurity in most commercial aluminum alloys, and it can have deleterious effects on fracture toughness and corrosion resistance [5]. In 6013, iron participates in the formation of an intermetallic α(AlFeMnSi) phase during solidification. Iron can be present in amounts up to about 0.6%, but a level below 0.4% is preferable [1]. For optimum toughness, it is preferred that the total amount of iron plus manganese be less than 0.9% by weight [1]. The amount of iron is a factor which needs to be considered when modifying the composition of 6013. A small amount of iron can also be found in α(AlMnSi) dispersoids.

From the considerations previously described, it is seen that any attempt to improve the performance of 6013 via the adjustment of composition is limited primarily to variations in the manganese and iron levels. The amounts of magnesium and silicon contents are fixed; the largest amount of copper that can be tolerated while maintaining acceptable corrosion resistance is added in order to optimize strength. Preliminary investigations [6-10] indicated that the degree of recrystallization of compositional variant of 6013 is strongly influenced by the volume fraction of Mn-dispersoids, which increases with increasing manganese content. A separate paper [11] will deal with the effect of manganese and iron, the effect of zirconium addition, the effect of preheat temperature, and the effect of solidification rate on the microstructure evolution and recrystallization behavior of 6013.

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