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Qingcai Liu

C. Lu

Joseph William Newkirk
Missouri University of Science and Technology, jnewkirk@mst.edu

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Progress in effect of Jominy end quench on the microstructure and mechanical properties of cast aluminum alloys*

LIU Qing-cai[1], WEI Chun-mei[1], LU Cun-fang[1], J.W Newkirk[2]

(1. School of Material Science and Engineering, Chongqing University, Chongqing 400044, China;

2. Department of Metallurgical Engineering, University of Missouri-Rolla, Rolla MO 65409, USA)

Abstract: In this review, the current knowledge related to the relationship between the heat treatment process and the microstructure and mechanical properties of A356 aluminum alloys are summarized. The review also examines the use of the Jominy end quench (JEQ) specimen and its application to the examination of the effects of quench rate and subsequent processing. Using the design of experimental methods combined with the Jominy end quench technique, desired changes in microstructure and mechanical properties of alloys can be obtained. So, the experimental technique of the Jominy end quench was concerned in this work.

Key words: Jominy end quench; cast aluminum alloys; microstructure; mechanical properties

1. Introduction

Aluminum and its alloys are characterized by light weight, a good strength-to weight ratio, excellent corrosion resistance, ease of fabrication, and reasonable cost. Their strength can be increased by alloying, cold working and by precipitation hardening. Cast and wrought aluminum alloys are produced in a wide range of forms[1]. Many alloys respond to thermal treatment based on phase solubilities. These treatments include solution heat treatment, quenching, and precipitation, or age and hardening. For either casting or wrought aluminum alloys, such alloys are described as heat treatable. But some casting aluminum alloys are essentially not heat treatable and are used only in as-cast or in thermally modified conditions unrelated to solution or precipitation effects. This presentation discusses the alloys that are heat treatable. In general, the purpose of heat treatment is to improve their mechanical properties, although in some cases heat treatment is asked for in order to relieve casting stresses[2]. The application of casting aluminum alloys has improved the automotive industry significantly in recent years. Consequently, the heat treatment of casting aluminum alloys for automotive applications is receiving considerable attention. Current technology uses convective solution treating; air, water or polymer quenching, and convective aging equipment to achieve a T6 or T7 heat treatment[3].

Aluminum alloys are heat treated for various times and at temperatures to produce desired changes in both microstructure and properties. Some of Heat treatment for aluminum alloys operations may be preceded or followed by mechanical working[4-7]. The most common particles found in cast alloys, when stabilized, are Mg_2Si and Al_2Cu. The steps involved in heat treatment are solubilization, quenching and aging. Solubilization is conducted at a temperature high enough to put in solution the different components in the alloy, which, in the case of complex aluminum casting alloys, it is normally done at temperature around 500℃. Quenching is carried out in air, an aqueous polymer solution or hot or cold water[8].

The purpose of heat treatment for an aluminum alloy is commonly to increase the hardness and strength of a given alloy, but other characteristics such as the decrease of internal stresses or improvement in

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Corresponding author: LIU Qing-cai, professor. E-mail: liuqc@cqu.edu.cn.

machinability can also be attained[9]. In order to improve the mechanical properties and satisfy the requirements of production, a lot of research and effort have been expended toward casting aluminum alloys[10-14]. The research and testing of heat treatment technology and optimizing parameters have made great progress in improving the mechanical properties and quality of aluminum alloy castings. But there are also encountered difficulties and challenges in the heat treatment of the casting aluminum alloys. D. Irani, et al[3] explained some practical approaches taken to face the challenges in the heat treatment of aluminum alloy castings. Strontium and sodium produce equivalently modified structures when used correctly, but sodium levels are more difficult to control than those of strontium. Strontium can be added easily, and oxidation is much less severe. Phosphorus and antimony poison the modification effect of both strontium and sodium and therefore should be avoided. Sodium and strontium work well together. Sodium develops an undesirable overmodified structure when dissolved levels exceed 0.02% by weight, and consistent results are hard to attain. Strontium contents in excess of 0.12-0.2% in casting alloys have been observed to develop the intermetallic compounds $SrSi_2$ and $SrAl_2Si_2$. It is proposed that a systematic study of the effect of heat treatment variables on the properties can be carried out successfully using the design of experimental methods combined with the Jominy End Quench technique (JEQ)[15]. JEQ has the effect of eliminating noise from the heat treatment due to the consistent heat treatment possible for a single sample. It has been used to study the heat treatment of thick plate for Century Aluminum of West Virginia. The goal was to improve the uniformity of the properties from the surface to the center and to increase the properties overall of plates up to 8" thick.

The JEQ and design of experiments were used to sort out the effects of eight different heat treatment variables on the properties. Studies of cast aluminum alloys with these methods should have a good chance of success. The difficulties imposed by the effects of solidification on the microstructure and chemistry will add complex factors to the work. These difficulties should be able to be overcome by some additional development of the techniques. The potential is great for making significant improvement in aluminum alloy castings by optimizing heat treatments. The cooling behavior of the cast parts could be characterized and the properties predicted by using the Jominy end quench data. Combinations of heat treatment parameters could be determined that provide maximum, uniform properties in a given part[15].

2. Quench sensitivity of aluminum alloys

An understanding of the mechanisms and causes of quench sensitivity are very important to developing alloys that are capable of thicker sections, and to allow the use of slower quenchants or quench factors to reduce the resulting residual stresses. Holl[16] evaluated the effects of minor alloying elements addition on the quench sensitivity of Al-Zn-Mg-Cu alloy. The age hardening behavior of the alloys was evaluated as a function of the cooling rate through the temperature range of 400-200℃. It was found that Cr, V, Mn, and Zr increased the quench sensitivity of the alloy, with Cr showing the greatest effect. Commercial impurities such as silicon and iron increased the quench sensitivity and should be minimized. Alloys with a lower solute supersaturation exhibit the lowest quench sensitivity. Alloys with high zinc-to-magnesium ratios allow solute supersaturation to be reduced without hurting the age hardening capacity.

Suzuki, et al[17] tested 7050 alloys containing 0-0.16% Zr. These alloys were treated in different manners. Hardness and resistivity measurements indicated that the nose of the TTT curve was about 350℃ and was independent of the Zr content. TEM examination showed that precipitation of Zr alloys was enhanced. The quench sensitivity of the alloys containing Zr was found to be ruled by the heterogeneous precipitation of η or T phase on Zr rich compounds. These compounds were found not to have an L12 structure and were incoherent with the matrix. The precipitation sites increased with the percent reduction from cold rolling after hot extrusion and prior to solution heat treatment. Suzuki, et al[18] also studied the quench sensitivity of Al-Zn-Mg-Cu alloys containing 0.2%Cr, 0.2%Zr and 0.24%-4% Hf., respectively by means of hardness, electrical resistivity measurements and electron microscopy. Specimens were cold-rolled before solution-treatment. The results showed that only in the alloy containing Zr or Hf quench sensitivity increased with increasing reduction. The highest quench sensitivity of the alloys examined was always the Cr containing alloy, irrespective of working.

Bryant and Thomas[19] investigated hot working and the resulting microstructure and quench sensitivity. During processing a length of a “T” shaped extrusion of 74S, it was found that the properties varied along the length of the extrusion. The tail end of the extrusion was found to have inferior properties. The heavy section extrusion had a different microstructure, and the poor properties were associated with microstructure that had poor quench sensitivity. These microstructures were found on the periphery of the extrusion, which were more prominent at the tail end of the extrusion.

3. Quench hardening of casting aluminum alloys

The mechanical properties of the crystal are largely determined by the number and mobility of dislocations contained in them. The mobility of dislocations is determined by their interaction with other defects. If the non-equilibrium concentrations of points defects are produced by rapid cooling from high temperature, the resulting hardening is called quench hardening[20]. But the quench hardening characteristics of quenched aluminum are not as sensitive to quenching temperature as those in copper and gold. Voids, dislocation loops and heavily jogged dislocation are seen in quenched and aged aluminum[21-23].

Cost-effective fabrication of high strength aluminum alloy castings is in dire need of a systematic method for determining the appropriate production configuration. The aluminum industry reluctantly acknowledges that a large fraction of production cost is associated with post-treatment operations. Typically, an aluminum extrusion is quenched by an array of high pressure water sprays upon exiting the extrusion die. This cooling process influences the internal microstructure of the alloys and the final metallurgical and mechanical properties[24]. An inferior quenching operation may result in parts having high residual stresses, non-uniform properties, low corrosion resistance, warping and soft spots all of which may lead to low strength and premature part failure.

Study results showed[24-25] that a successful heat treatment, including quenching treatment, alters the metallurgical structure of the aluminum alloy castings so that acceptable mechanical properties are obtained in the final products. Achieving superior hardness and strength in aluminum alloys demands very rapid quenching followed the solution heat treatment. The quench rate must be high enough to retard precipitation of the alloying elements so that controlled precipitation may occur during aging.

But rapid quenching may distort thin products and introduce detrimental residual stresses in thick ones. The magnitude of quenching stresses may be reduced by decreasing the cooling rates, but this approach may result in precipitation of the solute during cooling, and lowered strength and corrosion resistance. Since precipitation kinetics depend on both the degree of supersaturation and diffusion rates, which vary in opposite ways with temperature, a critical temperature range exists where nucleation and growth is maximum. A quenching process following the solution treatment is an important and effective step for improving the mechanical properties of cast aluminum alloy parts. The influence of the quenching on the structure and mechanical properties is also sensitive for the cast aluminum alloys. A successful quenching operation is determined by the selection of optimization parameters, such as cooling rate, temperature and quenchant.

4. Heat treatment of A356 cast aluminum alloys

Cast 356 aluminum alloys have widespread applications in the general engineering, automotive, and aerospace industries. This alloy exhibits excellent castability, good mechanical properties, corrosion resistance, weldability, and low thermal expansion [26-27].

The mechanical properties of the A356 cast aluminum alloy are affected significantly by the morphology of eutectic silicon and other alloy elements. The addition of small amounts of sodium, strontium, or antimony modifies the morphology of the silicon from acicular to fibrous or lamellar shape, thereby improving the mechanical properties of the alloy[28-29]. Modification by Na also improves the feeding characteristics of the melt in both sand and metal molds[30]. Dissolution of Na is instantaneous at the processing temperature, but because of the very high vapor pressure, a large fraction of Na added boils off almost immediately, leading to the so-called 'fading' and poor recovery[27,31]. Strontium fades at a lower rate than Na and does not overmodify the Si when present in excess, unlike Na. However, if present in larger amounts, Sr can result in the formation of undesirable intermetallic compounds such as $SrSi_2$ and $SrAl_2Si_2$. Besides, Sr necessitates longer incubation periods for effective modification[32].

T. Takaai, et al[33] investigated the effects of heat treatment on certain mechanical properties and the fracture toughness of A356 aluminum casting alloy. A356 casting is mainly used as wheels for passenger car applications, has been experimentally studied. The studies examined relationships between the heat treatment conditions, such as solution treatment, aging temperatures, time, etc. and obtained mechanical properties or microstructures. Solution treatments and aging at relatively higher temperatures promoted sufficient precipitations and spherodization of the eutectic silicon structure resulting in improvement of the 0.2% proof stress and fracture strength. Absorbed energies by Charpy impact test and tensile elongation to fracture, however, were not so significantly improved.

Microporosity formation in production casting has limited their application in safety critical components for automobile chassis and airframe structure[34]. Microporosity usually results from the failure of interdendritic, feeding, exsolution of dissolved gas from melt, or a combination. It has been shown that the final amount, size, and distribution of voids in aluminum alloy casting is determined by several factors[34-36] , such as initial gas content in the melt, grain structure, processing conditions (cooling rate, thermal gradient, solidification time, and external pressure), melt composition, and inclusion content[37]. Microporosity is a traditional problem in aluminum castings. In the past decade, much effort has been devoted to the modeling of microporosity formation and growth. And some investigations for modification treatment to microporosity have been done[36]. It is well know that modification treatments with Na and Sr increase the propensity to microporosity formation. In modified melts, most microporosities are round, while in unmodified melts pores are irregular.

A quenching-during-modification technique, in modified (Na and Sr) and unmodified 356 aluminum alloys, was used to observe the fraction of solid at which the pore uncleation of the pore morphology[38]. The melts were prepared in a gas-fired furnace with an 8kg capacity graphite crucible, using a 356 masteralloy as charge material. Each melt was refined with 0.10% titanium added as Al-Ti-B (5:1) masteralloy. Metal treatment, when used, was made with additions of 0.10% metallic sodium, 0.03% strontium as Al-Sr(10%Sr) masteralloy or 0.25% metallic antimony. The dissolution time was 20 minutes for Sr-and Sb-treatments. After the melt treatment, the hydrogen content was controlled to a fixed amount of 0.13ml H_2/100g Al, using Telegas equipment and Alscan probes. The results show that in the modified melts, the pore nucleation starts earlier than in the unmodified ones, while in Sb-refined melts the nucleation is delayed. The differences in final pore morphology could be explained by the fraction solid in which pores nucleated and by the type of eutectic cell/liquid interface.

The study of the application of quench factors to A356.0 and A357.0 foundry alloys[39] showed that quench factors can be calculated and used to determine a cooling rate which minimizes quenching stresses for a given minimum yield strength requirement. The current work has produced both time-temperature-yield strength (TTY) curves and a methodology for the prediction of yield strength as a function of quenching rate for Al-Si-Mg casting alloys. The application of quench factor analysis to these alloys facilitates a deeper understanding of their quenching behavior and also enables the prediction and/or design of optimal industrial quenching procedures for given yield strength requirements.

Rare earth (RE) elements and mischmetal (MM) (mischmetal, a mixture of rare earth elements, such as La, Ce, Nd, Y etc.) were reported to be capable of modifying the eutectic structure in 356 casting alloy[40-45]. Modification with RE elements was explained using the critical growth temperature hypothesis, in which the modifying element should exhibit a tendency to form compounds with the precipitating phase(Si) at a temperature below the normal eutectic temperature, and should also exhibit little compound-forming tendency with the solvent phase. RE elements have been added to 356 alloy as MM and in the form of specific RE metals and as fluorides[46]. Eutectic undercooling in a 356 alloy is increased by as much as 25 K, with an increase in MM addition up to 2 pct, and complete modification is obtained[47].

Unfortunately, there are a lot of problems in the experimental design, discrimination of the test parameter, heat treatment technology and the controlling of the structure of the A356 alloys. For example, the modification and other treatments present the side effect of intensifying the tendency to microporosity formation. The processing details are not recorded in terms of the optimum quantity of MM to be added to this alloy and its effect on structure and properties.

5. Summary

As we known, heat treatment can improve the microstructures and mechanical properties of the cast aluminum alloys greatly. After heat treatment, desired changes in microstructure and properties of alloys can be obtained to satisfy the requirements for different applications of casting parts. There are many factors that influence the results of heat treatment. Designing, controlling and performing the heat treatment properly is a major problem. It is essential to develop an optimized heat treatment for cast aluminum alloys.

The expected results of heat treatment for cast aluminum alloys in a laboratory environment of small samples of well-characterized chemistries can be predicted easily with a minimum amount of experimentation. But, as section sizes increase and commercial chemistries are used in the production environment, the ability to predict the resulting mechanical properties decreases significantly. When these problems are accompanied with the non-uniformity of microstructure and chemistry found in typical castings, as well as the more complicated quenching behavior of complex part shapes, then consistent results are difficult to obtain. Studies for the effect of heat treatment parameters on the mechanical properties are also difficult to carry out due to a lot of variables, and experimental noise in the process of heat treatment confounds the results[15]. Development of optimized heat treatments for cast aluminum alloys is very important and useful.

The JEQ test can offer a method for studying many quenching condition with a minimum of samples. It uses a 1" cylindrical bar to incorporate a large range of cooling rates in one test sample. Cooling from the end gives a continuous range of quench rates that can be used to compare cooling rates in a given part's geometry. The sample can then be heat-treated to a given set of conditions. This is a tremendous advantage over attempting the same study with individual samples. The bar is the same composition, heat lot, same solution heat treatment, same age time and temperature. The only variable is the quench rate. It also has the effect of eliminating noise from the heat treatment due to the consistent heat treatment possible for a single sample[15,48-49].

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