

DEVELOPMENT OF HEAT TREATMENT PROCESS THROUGH MICROSTRUCTURAL CONTROL IN 2017 ALUMINUM ALLOY FOR AEROSPACE APPLICATION

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ABSTRACT

The 2017 aerospace aluminum alloy was characterized through metallographic investigations. A series of precipitation strengthening and age-hardening heat treatment processes involving solution treatment at 550 °C followed by quenching (and tempering for various time-durations) were conducted for the 2017 alloy. Micro structural characterization of the heat-treated samples showed effective distribution of fine θ' particles in the α -matrix of the aluminum alloy; these micro structural features enable us to develop proper precipitation strengthening and age-hardening heat-treatment process parameters for the 2017 aluminum alloy for aerospace application.

Key words: 2017 aluminum alloy, precipitation strengthening, age hardening, microstructure

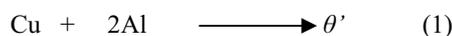
1. INTRODUCTION

The 2xxx series age-hardenable aluminum alloys are extensively used in aircraft structures owing to their good specific strength and lightweight (Ibrahim Ozbek, 2007; Xie *et al*, 1998; Huda *et al*, 2006). The 2017 aluminum alloy, in the as-rolled condition, is unsuitable for aerospace application since it lacks strength and ductility owing to elongated grains, regions of high energy, and absence of dispersed second-phase particles in its microstructure. These micro structural features require proper precipitation-strengthening or age-hardening heat treatment to be given to the alloy for aerospace application [Kacer *et al*, 2003; DeGarmo *et al*, 2003].

The feature of great metallurgical importance in 2xxx series aluminum alloys is their abilities to improve mechanical properties when suitably heat treated. Aluminum-copper alloys (for aerospace applications) are usually given special heat treatments, called age-hardening which are process of strengthening metals based on θ' -particles strengthening. For the process to occur, it requires certain phase transformations resulting from either precipitation strengthening or age hardening heat treatment involving solution treatment, quenching and tempering (John, 1990).

The aluminum-rich portion of Al-Cu equilibrium phase diagram enables us to determine solution-treatment

temperature for age hardening of the Al-Cu aerospace aluminum alloy. If the Al-Cu alloy (containing less than 5.7%Cu) is slowly heated at above-solvus temperature (and below liquidus temperature), the particles of CuAl_2 are absorbed until we obtain a single-phase solid solution comprising of α -phase. On quenching the alloy, we retain the copper in solution, and in fact, produce a supersaturated solution of copper in aluminum at room temperature. If the quenched alloy is allowed to remain at room temperature, it is found that strength and hardness gradually increases and reaches a maximum in several days. The completely α -phase structure obtained by quenching is not the equilibrium structure at room temperature. It is in fact supersaturated with copper, so copper atoms diffuse out according to the following phase transformation:



The θ' precipitate refers to intermediate coherent precipitates of CuAl_2 . The precipitation of θ' (see Equ 1) in the microstructure of the 2xxx series Al-Cu alloy greatly increases strength renders the material suitable for aerospace applications (Askland and Phule, 2003).

The objectives of the research reported in the paper include development of suitable precipitation-strengthening and age-hardening heat-treatment processes with specified parameters for the 2017 alloy for aerospace applications. An attempt is also made to study the effect of solution treatment followed by slow cooling and the effect of overheating on solution-treated and quenched alloy on its microstructure and hardness.

2. EXPERIMENTAL WORK

The starting material (SM), of 2017 aluminum alloy plate, was purchased from local market. The chemical composition of the 2017 aluminum alloy is shown in Table 1. Five metallographic samples were sectioned from the SM by use of a hacksaw at slow cutting rate so as to avoid any thermal effect on microstructure. Four (4) out of the 5 samples were heat treated in an atmosphere-controlled furnace according to the sample-identification scheme presented in Table 2.

Table 1: Chemical composition of the 2017 aluminum alloy

Element	wt%
Cu	4.3
Si	0.4
Fe	0.7
Mn	0.6
Mg	0.6
Zn	0.25
Cr	0.1
Ti	0.15
Al	Balance

Table 2: Sample identification scheme according to heat treatment

Heat Treatment Process	Sample Id #
As-received material	A-0
Heated to 550 °C then slowly cooled	B
Heated to 550 °C, quenched, aged for 2 days	C
Heated to 550 °C, quenched, tempered 165 °C/10 h	D
Heated to 550 °C, quenched, tempered 200 °C/10 h	E

Five metallographic samples were mounted by cold mounting technique. Metallographic specimens for the 5 samples were prepared by metallographic grinding (with 800, 1000, 1200, and 1500 grit size silicon carbide emery papers) and polishing (using high alumina powder) followed by metallographic etching by use of Keller's reagent (150 ml water, 3 ml HNO₃, 6 ml HCl, and 6 ml HF). In order to characterize microstructure, an optical (metallurgical) microscope linked with a computerized imaging system was used. The computerized imaging system is run by the MSQ software. The microscope is facilitated with a sophisticated camera system to capture images of the as-received as well as heat-treated samples of the investigated alloy. A Vickers hardness testing machine was used to determine hardness values before and after heat treatment of the 2017 alloy.

3. Results and Discussion

3.1 Hardness Test Results & Analysis

The results from Vickers hardness testing machine for the samples (A-E) (see Table 2) are presented as a column chart in Fig 1. The analysis of data in Fig 1 clearly indicates the highest hardness for sample A-0 and the lowest hardness for sample E. The excessively high

hardness (poor ductility) in the sample A-0 is thought to render the as-received material to be unsuitable for aerospace application (Heinz *et al.*, 2000). On the other hand, hardness values for samples B and C are undesirably low indicating poor strength. However, samples C and D have intermediate hardness values (see Fig 1); and appear to possess adequate strength for aerospace application. This fact is discussed with reference to micro structural analysis in subsequent sub-sections.

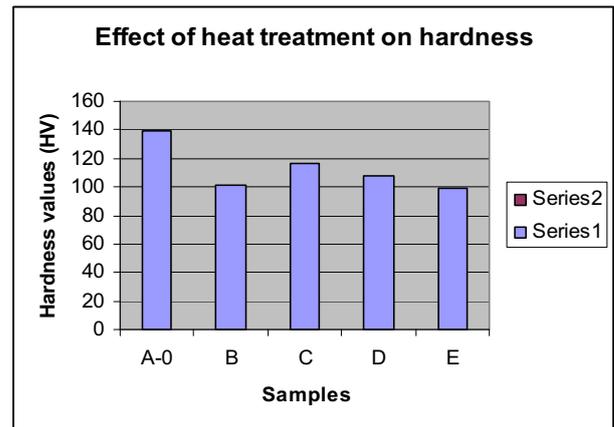


Fig 1: Column chart showing effects of heat treatment on hardness of 2017 aluminum alloy

3.2 Microscopic Results and Analysis

The microstructures of the 2017 aluminum alloy before and after heat treatment are shown in the optical micrographs in Figs. 2(a-e).

3.2.1 Microstructure and Performance of As-received Material

The microstructure of the as-received 2017 aluminum alloy is shown as optical micrograph in Fig 2(a); which clearly shows elongated grains.



Fig 2(a) Microstructure of the as-received aluminum alloy (sample A-0)

This micro structural feature in the as-received alloy indicates that the starting material was received in the un-recrystallized form. The elongated grains also represent high-energy regions within the material resulting from cold rolling. The high-energy regions in the deformed metal are thought to have reduced ductility properties of the as-received material. This fact is confirmed by the high hardness value (139 HV) of the as-received material (see Fig1). Hence, it is quite logical to conclude that the as-received material lacks ductility and toughness and is unsuitable for aerospace application (Askland and Phule, 2003; Heinz *et al*, 2000).

3.2.2 Effect of solution treatment followed by slow cooling

Figure 2(b) represents the microstructure of the 2017 Al alloy resulting from solution treatment followed by slow cooling (sample B). The optical micrograph in Fig 2(b) shows dual-phase microstructure consisting of α -matrix and precipitation of θ phase along grain boundaries in the alloy. The θ phase represents CuAl_2 (inter-metallic compound); which forms as non-coherent precipitate. The presence of non-coherent particles/phase of CuAl_2 will cause the material to become weak because only 0.2% Cu is left in solution (Askland and Phule, 2003; Higgins, 1980). This micro structural interpretation is in accordance with the fall in hardness value of sample B as compared to sample A-0 (hardness value falls from 139 to 101 HV) (see Fig 1). Hence, it is justified to conclude that the alloy resulting from solution treatment at 550 °C followed by slow cooling to room temperature lacks strength and is also unsuitable for aerospace application.



Fig 2(b) Microstructure of aluminum alloy heated to 550 °C then slowly cooled (sample B)

3.2.3 Effect of Age-hardening (Natural Aging)

A look at Table 2 indicates that sample C represents age-hardened alloy i.e. the alloy resulting from solution treatment at 550 °C, quenching and then cooling at room temperature (30 °C) for 2 days. The microstructure of the age-hardened alloy (sample C) is shown in the optical micrograph in Fig 2(c). In fact, solution treatment at 550 °C produces a supersaturated α phase; which is a non-equilibrium phase. On natural aging, a second phase

(CuAl_2) (θ') has diffused out from the earlier supersaturated state after aging for 2 days (see Equ (1)). Since the supersaturated state resulting from quenching is not the equilibrium state, the copper atoms diffuse out from aluminum lattice and form a coherent θ' and the fine dispersion of precipitates within the grains (see Fig 2(c)). The strengthening imparted by the dispersed precipitates in the age-hardened alloy can be verified by the rise in hardness value from 101 to 116 HV for sample C (see Fig. 1). These micro structural features and hardness test analysis lead to a conclusion that the strength of the naturally-aged alloy is good enough for aerospace application (Askland and Phule, 2003; Heinz *et al*, 2000; Higgins, 1980; Gayle & dway, 1994).

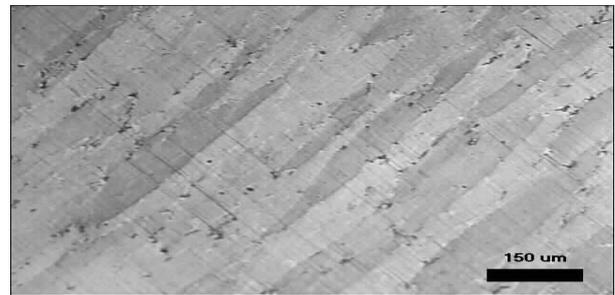


Fig 2 (c) Microstructure of age-hardened aluminum alloy heated to 550 °C, water-quenched then cooled at room temperature (30 °C) for 2 days (sample C)

3.2.4 Effect of Precipitation Strengthening (Artificial Ageing)

Figure 2(d) shows microstructure of precipitation-strengthened aluminum alloy (sample D); here a second phase also precipitates as the intermediate coherent precipitates of CuAl_2 (θ'). The fine particles of θ' phase effectively impede the movement of dislocations and hence impart strength to the alloy (Askland and Phule, 2003; Heinz *et al*, 2000; Higgins, 1980; Gayle & dway, 1994; Bishop 1967; Huda *et al*, 2009).

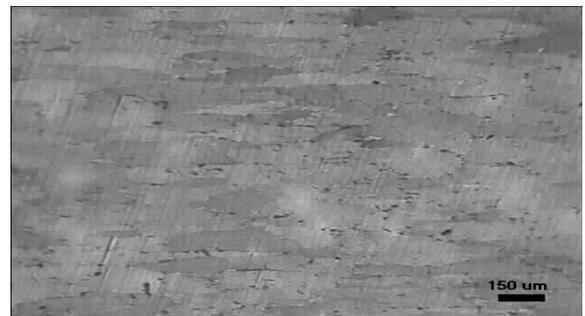


Fig 2(d) Microstructure of precipitation-strengthened aluminum alloy heated to 550 °C, water-quenched then tempered 165 °C/10 h (sample D)

Figure 1 indicates a slightly lower hardness value of sample D (108 HV) in comparison to sample C (116 HV)

(see Fig 1); however this slightly lower hardness value does not necessarily indicate lower strength. In fact, microstructure of sample D (see Fig 2 (d)) shows quite effective dispersion of θ' particles; and hence advocates both good strength as well as better ductility. This microstructure interpretation is in agreement with literature; according to which a high tensile strength of 470 MPa was imparted in a similarly-treated Al-4%Cu alloy (Heinz *et al.*, 2000). It is, therefore, quite logical to conclude that the artificial ageing heat treatment given to the alloy (sample D) is the optimum precipitation strengthening parameters to render the material suitable for aerospace application.

3.2.5 Effect of Overheating tempering on quenched alloy

The effect of overheating tempering on the solution-treated and quenched alloy is shown in the micrograph in Fig 2(e). The microstructure of sample *E* reveals coarse particle phase; it means tempering at a higher temperature has caused precipitation of coarse θ'' phase which is non-coherent to matrix (Askland and Phule, 2003). This microstructural feature indicates loss in strength; which is confirmed by a low hardness value (99 HV) for the sample E (see Fig1). This material behavior and microstructural feature of the over-heated quenched alloy confirms that the strength of the alloy (sample E) is poor; and hence the material is unsuitable for aerospace application.

4. CONCLUSIONS

The metallographic and hardness testing investigations for 2017 aerospace aluminum alloy lead us to draw the following conclusions:

- a) The microstructure of 2017 aluminum alloy resulting from solution treatment at 550 °C followed by slow cooling to room temperature indicates low strength and is unsuitable for aerospace application.
- b) Natural ageing (age hardening) involving solution treatment at 550 °C, water-quenching followed by ageing at room temperature (30 °C) for 2 days (48 h) imparts adequate strength to the alloy; and renders the material suitable for aerospace application.
- c) Artificial ageing (precipitation strengthening) involving solution treatment at 550 °C, water-quenching followed by tempering at 165 °C for 10 hours results in effective dispersion of fine θ' -phase particles in the microstructure; and was found to be the optimum precipitation strengthening parameters to render the material suitable for aerospace application.

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