International Journal of Materials Engineering 2015, 5(1): 5-9
DOI: 10.5923/j.ijme.20150501.02

Effect of As-Cast Cooling on the Microstructure and Mechanical Properties of Age-Hardened 7000 Series Aluminium Alloy

Isadare D. A.[1,2], Adeoye M. O.[2], Adetunji A. R.[1,2], Oluwasegun K. M.[2], Rominiyi A. L.[1], Akinluwade K. J.[1,2,*]

[1]Department of Engineering, Prototype Engineering Development Institute Ilesa, [National Agency for Science and Engineering Infrastructures, NASENI Abuja]
[2]Department of Materials Science and Engineering, Obafemi Awolowo University, Ile-Ife

Abstract This study investigates the influence of as-cast cooling on the microstructure and mechanical properties of age-hardened Al-Zn-Mg-Cu alloy. The material was cast in the form of cylindrical rods in green sand mould where some samples were rapidly cooled and others gradually cooled to room temperature. From the samples that were gradually cooled, some were annealed while others were T6 tempered. Both the as-cast and heat treated samples were subjected to tensile and hardness tests and the morphology of the resulting microstructures were characterised by optical and scanning electron microscopy. The results revealed formation of microsegregations of $MgZn_2$ during gradual solidification which was not present during rapid cooling. It was also found that age hardening and annealing heat treatment operations eliminated microsegregations thus improving mechanical properties of Al-Zn-Mg-Cu alloy.

Keywords Al-Zn-Mg-Cu alloy, Microsegregation, Age hardening, Annealing, Strength

1. Introduction

The demand for aluminium grows rapidly because of its unique combination of properties which makes it one of the most versatile engineering and structural materials [1-3]. The optimum properties of aluminium are achieved by alloying and heat treatments. These promote the formation of coherent precipitates which interfere with the movement of dislocations and improve its mechanical properties [4-7]. One of the most commonly used aluminium alloy for structural applications is the 7075 Al alloy due to its attractive properties such as low density, high strength, ductility, toughness and resistance to fatigue [8-11]. It has been extensively utilized in aircraft structural parts and other highly stressed parts [12-16].

Nevertheless, aluminium-zinc alloys are susceptible to embrittlement because of microsegregation of magnesium zinc ($MgZn_2$) precipitates which may lead to failure of components produced from them [17, 18]. These alloys are also susceptibility to stress corrosion cracking [19, 20] due to inhomogeneity and inherent residual stresses associated with their fabrication methods [21]. These microsegregations and inherent residual stresses have serious deleterious effects on mechanical properties [18]. Hence, this study aims at resolving the problems of microsegregations and inherent residual stresses that are associated with aluminium-zinc alloys, for improved performance in service. The aim of this work is to investigate the influence of as-cast cooling on the structure and mechanical properties of T6 tempered 7000 series aluminium alloy via annealing and age hardening heat treatment processes.

2. Materials and Method

The elemental composition of the 7000 series Al alloy used for this study is shown in Table 1. The material was cast in the form of cylindrical rods. Some of the cast rods were rapidly cooled to room temperature by knocking them out 5 minutes after casting while others were cooled gradually inside the mould. Tensile samples were machined from these categories of rods according to British Standard BSEN 10002-1:1990 [22]. Samples were also sectioned for metallographic and micro hardness tests.

Age hardening and annealing heat treatments were carried out on samples machined from slowly cooled castings. Annealing was carried out on samples prepared for metallographic analysis and hardness test. These samples were heated to 470 °C, soaked at this temperature for 4 hours

* Corresponding author:
jakinluwade@yahoo.com (Akinluwade K. J.)
Published online at http://journal.sapub.org/ijme

and then furnace cooled. Age hardening was carried out by solution treatment of another set of samples prepared for metallographic and hardness test at a temperature of 465 °C for 4 hours followed by quenching in cold water. The quenched samples were subjected to aging by heating them to 140 °C, holding at this temperature for 5 hours then air cooling to room temperature (i.e. T6 tempered).

Tensile test for all specimens was carried out in accordance with the British Standard BSEN 10002-1:1990 [22]. The tensile test was carried out at room temperature at a strain rate of 5 mm/min using Instron 3369 electromechanical testing machine. Proof stress, ultimate tensile strength, elastic modulus and percentage elongation values were obtained. Hardness test was done using the LECO ASTM E384 micro hardness tester, at 5 different points on each sample with a test load of 490.3 mN over a dwell time of 10 s. The average hardness value was estimated and recorded. The samples for microscopy were grinded with graded emery grit papers (400 – 1200) and polished with 10, 7, 5, 3.5, 2.5, 1.5, 1 and 0.5 micron diamond pastes followed by etching with a freshly prepared Keller's solution (1.0 ml HF, 1.5 ml HCl, 2.5 ml HNO_3, and 95.0 ml H_2O).

Table 1. Elemental Composition of 7000 Series Al alloy used.

Element	Mg	Zn	Cu	Fe	Cr	Ni	Mn	Al
Weight %	2.45	5.36	1.43	0.11	0.01	0.02	0.02	Balance

3. Results and Discussion

Figures 1 to 4 show the micrographs of samples under conditions of slow cooling, rapid cooling, annealing and age-hardening (T6 tempered) respectively. Figure 5 is the scanning electron micrograph of T6 tempered sample. The microstructure of as-cast but slowly cooled sample shows microsegeregation of $MgZn_2$ in aluminium matrix while as-cast but rapidly cooled sample shows fine grains of $MgZn_2$ phase which is uniformly distributed in the aluminium matrix. The microstructure of annealed sample shows dissolved $MgZn_2$ phase which is non-uniformly distributed in the aluminium matrix while the microstructures of age-hardened sample (Figures 4 and 5) show the finely dispersed precipitates of $MgZn_2$ in aluminium matrix. The presence of dispersed precipitate of $MgZn_2$ corresponds with the result of Salamci [23] and Du *et al*. [24] who discovered that aging heat treatment of Al-Zn-Mg-Cu alloys led to formation of $MgZn_2$ intermetallic phase in the structure.

In their study on evolution of eutectic structures in Al-Zn-Mg-Cu alloys Fan *et al*. [25], reported that several coarse intermetallic phases such as $MgZn_2$, $Al_2Mg_3Zn_3$, AlCuMg, Al_2Cu, $A_{l7}Cu_2Fe$, $Al_{13}Fe_4$ and Mg_2Si can be formed below the solidus line during solidification of as-cast 7000 series aluminium alloys as a result of solute redistribution of metals. This report supports our finding of microsegeregation of $MgZn_2$ in slowly cooled samples.

In a rapidly cooled sample, there was no room for solute redistribution of Mg and Zn and hence microsegregation of $MgZn_2$ was not formed. However, during the soaking period of heat treatment operations, the microsegregations formed after slow cooling are dissolved to form a homogeneous phase and they disappeared after subsequent cooling.

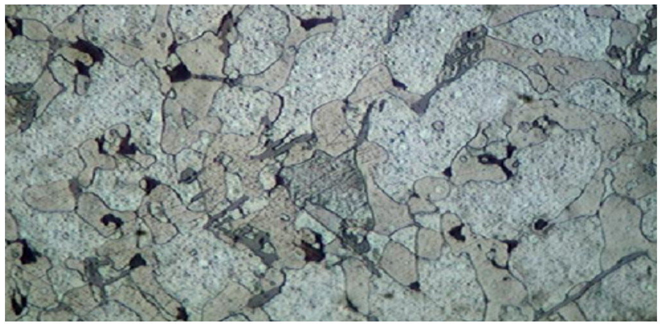

Figure 1. Optical micrograph of slowly cooled Al-Zn-Mg-Cu alloy, x200

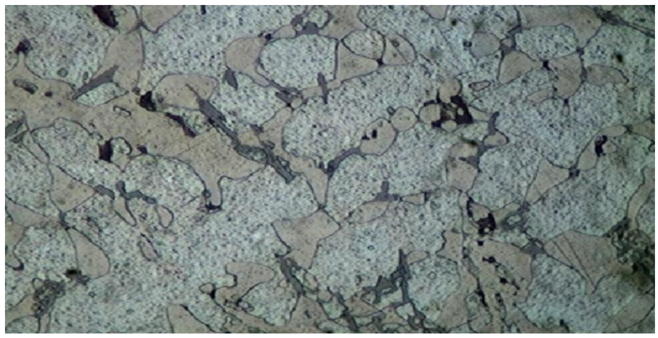

Figure 2. Optical micrograph of rapidly cooled Al-Zn-Mg-Cu alloy, x200

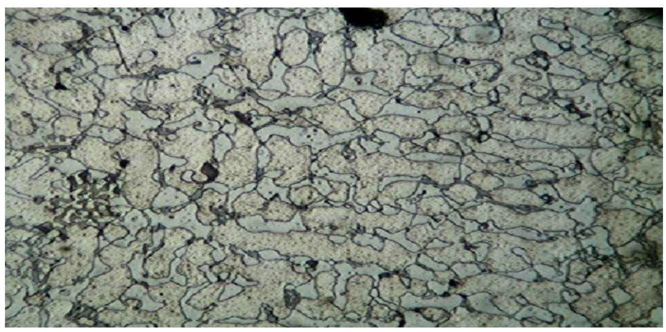

Figure 3. Optical micrograph of annealed Al-Zn-Mg-Cu alloy, x200

Figure 4. Optical micrograph of T6 Tempered Al-Zn-Mg-Cu alloy, x200

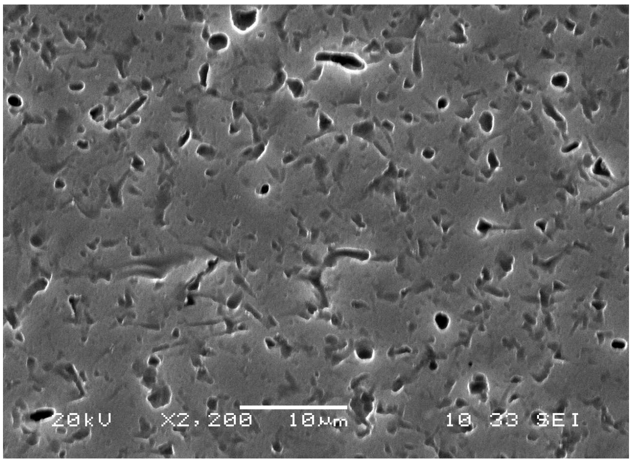

Figure 5. SEM micrograph of T6 Tempered Al-Zn-Mg-Cu alloy

The elimination of microsegregations after annealing and aging heat treatment operations in the present investigation is in agreement with the findings of Guo *et al*. [26] who found out that solution treatment markedly reduce the degree of microseregation in 2024 wrought aluminium alloy. Table 2 presents the mechanical tests results; the T6 tempered samples has the highest ultimate tensile and yield strengths followed by as-cast but slowly cooled samples, as-cast but rapidly cooled and annealed samples. The T6 tempered sample has the highest hardness and strength because of the presence of coherent $MgZn_2$ precipitates in its structure which was developed during aging. The reason for the observed trend in hardness and strength in the remaining samples is the variations in their grain size and morphology. This is in agreement with the findings of Kenji *et al*. [27] which indicated that solid-solution and grain refinement contribute to the hardening of Al-Mg alloys. Also, it is well reported in previous studies that fine-grained materials have more grain boundaries and are harder and stronger than coarse grained materials that have fewer grain boundaries [28-30].

Since age-hardened/T6 tempered sample has more grain boundaries than others (as-cast but rapidly cooled, as-cast but slowly cooled and annealed samples) there is more impediment to dislocation movement during deformation and hence it is harder and stronger [31].

The improvement in strength and hardness can also be explained from the microstructural perspective. The finer the grains, the more the grain boundaries. During plastic deformation, slip or dislocation movement must take place across these grain boundaries. Since polycrystalline grains are of different crystallographic orientations at the grain boundaries, a dislocation passing from one grain to another will have to change its direction of motion. Such changes of direction cause impediment to dislocation movement, and increase both the yield strength and ultimate tensile strength. Since age-hardened samples have the highest number of grain boundaries, dislocation movement becomes more and more difficult during plastic deformation. This is responsible for the observation of the highest yield strength and ultimate tensile strength in age-hardened samples. Also, Al-Zn-Mg-Cu alloy used for this study contains about 5.36 % Zn and 2.45 % Mg. These two alloying elements increased the strength of this alloy via the formation of coherent $MgZn_2$ precipitate within its structure during aging. This result tallies with Du *et al*. [24], Li and Peng [11], Demir and Gündüz [32] and Kaya *et al*. [33] who concluded that Al-Zn-Mg alloy can get the highest strength level in natural and artificial aging.

Annealed sample has the highest percentage elongation followed by as-cast but rapidly cooled, T6 tempered, and as-cast but slowly cooled samples. This is partly due to increase in grain coarsening which led to an increase in the grain boundary area that increased the amount of energy required for the movement of dislocations required to cause fracture [34-36]. Thus, the material can withstand a higher plastic deformation before the final fracture. However, the percentage elongation of as-cast but slowly cooled sample is the least due to the presence of badly shaped microsegregation of $MgZn_2$ in its structure (Fig. 1).

T6 tempered samples have the highest hardness followed by as-cast but slowly cooled, as-cast but rapidly cooled, and annealed samples. As-cast but slowly cooled sample has high hardness as a result of its brittle structure. The highest hardness values developed by age-hardened samples can be attributed to precipitation of coherent and finely dispersed $MgZn_2$ phases which serves as foreign inclusion in the lattice of the host crystal in the solid solution; this causes more lattice distortions which makes the alloy harder. In the previous study solid solution strengthening from elastic distortions is produced by substitutional atoms of Mg and Zn in aluminium matrix [37].

Table 2. Results of mechanical tests for as-cast and heat treated Al-Zn-Mg-Cu samples

Samples	Proof Stress (MPa)	UTS (MPa)	Elastic Modulus (MPa)	% Elongation	Hardness (VHN)
Rapidly cooled	182.56	205.54	11205.01	17	63.4
Slowly cooled	213.21	234.87	16230.84	11	85.2
Annealed	153.43	178.35	15489.89	20	55.6
T6 Tempered	255.55	297.89	15901.51	15	109.5

Hence, the main strengthening mechanism in these alloys is precipitation hardening by the structural precipitates of $MgZn_2$ formed during artificial aging. These precipitates act as obstacles to dislocation movement and thereby strengthen the alloys. The elastic modulus, which is a measure of the stiffness of a material and the theoretical strength of that material [38], was found low for rapidly cooled sample. This was as a result of weak bonds that formed during fast cooling of the alloy since there is no room for proper diffusion to take place unlike in slowly cooled, annealed and aged samples where there was no significant difference in elastic modulus. The precipitates formed during aging are stronger and are therefore more rigid and stiff.

4. Conclusions

The following conclusions can be drawn from the results of this work.

1) Gradual cooling of this alloy resulted in formation of microsegregations with its associated deleterious effects on the mechanical properties.
2) Rapid solidification process, annealing and T6 tempering heat treatment operations eliminated the formation of microsegregations and significantly improved mechanical properties.
3) T6 tempering heat treatment operation was found to improve hardness value, yield and ultimate tensile strengths with a corresponding decrease in ductility. On the other hand, annealing heat treatment operation improved ductility but lowered hardness value, yield and ultimate tensile strengths.
4) Annealing treatment for this alloy will be suitable for designs and applications that require high toughness and ductility while age hardening treatment will be suitable for designs that require high hardness value, ultimate tensile and yield strengths.
5) The results of this research work would also help in ameliorating intergranular and stress induced corrosions as a result of removal of grain boundary segregations and stress; but further research work is required to confirm this.

REFERENCES

[1] American Society for Metals - ASM. *Handbook. Properties and selection*. Nonferrous Alloys and Special-Purpose Materials ASM International Handbook Committee; 1990 vol. 2, p. 137-38.

[2] Machler R, Uggowitzer PJ, Solenthaler C, Pedrazzoli RM and Spiedel MO. Structure, mechanical properties, and stress corrosion behaviour of high strength spray deposited 7000 series aluminium alloy. *Materials Science Technology*. 1991; 7:447-51.

[3] Chee FT and Mohamad RS. Effect of hardness test on precipitation hardening aluminium alloy 6061-T6. *Chiang Mai Journal of Science*. 2009; 36(3):276-86.

[4] Smallman RE. *Modern physical metallurgy*. 4th ed. London: Butterworths & Co.; 1985.

[5] Lavernia EJ, Rai G and Grant NJ. Rapid solidification processing of 7xxx aluminium alloys: a review. *Materials Science and Engineering*. 1990; 79:211-21.

[6] Sanctis MD. Structure and properties of rapidly solidified ultrahigh strength Al-Zn-Mg-Cu alloys produced by spray deposition. *Materials Science and Engineering*. 1991; A141:103-21.

[7] White J, Mingard K, Hughes IR and Palmer IG. Aluminium alloys with unique property combinations by spray casting. *Powder Metallurgy*. 1994; 37(2):129-32.

[8] Heinz A and Haszler A. Recent development in aluminum alloys for aerospace applications. *Materials Science and Engineering A*. 2000; 280(1):102-7.

[9] Williams JC and Starke Junior EA. Progress in structural materials for aerospace systems. *Acta Materialia*. 2003; 51(19):5775-99.

[10] Clark R, Coughran B, Traina I, Hernandez A, Scheck T, Etuk C et al. On the correlation of mechanical and physical properties of 7075-T6 Al alloy. *Engineering Failure Analysis*. 2005; 12:520-6.

[11] Li JF and Peng ZW. Mechanical properties, corrosion behaviors and microstructures of 7075 aluminium alloy with various aging treatments. *Transactions of Nonferrous Metal Society of China*. 2008; 18(4):755-62.

[12] Woei-Shyan LS and Wu-Chung S. The strain rate and temperature dependence of the dynamic impact properties of 7075 aluminum alloy. *Journal of Materials Process and Technology*. 2000; 100:116-22.

[13] Lin G, Zhang H, Zhang X, Han D, Zhang Y and Peng D. Influences of processing routine on mechanical properties and structures of 7075 aluminium alloy thick plate. *Transactions of Nonferrous Metal Society of China*. 2003; 13(4):809-13.

[14] Shwe WHA, Kay TL and Waing KKO. The effect of ageing treatment of aluminum alloys for fuselage structure-light aircraft. *World Academy of Science*, *Engineering and Technology*. 2008; 46:696-9.

[15] Zhao T and Jiang Y. Fatigue of 7075-T651 aluminum alloy. *International Journal of Fatigue*. 2008; 830:834-849.

[16] Mohammad T and Esmaeil E. Mechanical and anisotropic behaviors of 7075 aluminum alloy sheets. *Materials and Design*. 2010, 32(2):1594-9.

[17] John VB. *Introduction to engineering materials*. London: Macmillan Press Limited; 1992.

[18] Meng-Shan T, Pei-Ling S, Po-We K and Chih-Pu C. Influence of severe plastic deformation on precipitation hardening in an Al-Mg-Si alloy: microstructure and mechanical properties. *Materials Transactions*. 2009; 50(4):771-5.

[19] Ramesh SK, Kondaiah G, Venkatachalam P and Ravisankar B. Stress corrosion cracking of Al 7075 alloy processed by

equal channel angular pressing. *International Journal of Engineering*, *Science and Technology*. 2010; 2(12):53-61.

[20] Silva G, Rivolta B, Gerosa R and Derudi U. Study of the SCC behavior of 7075 aluminum alloy after one-step aging at 163°C. *Journal of Materials Engineering and Performance*. 2012.

[21] Isadare DA, Aremo, B, Adeoye MO, Olawale JO, Shittu MD. Effect of Heat Treatment on Some Mechanical Properties of 7075 Aluminium Alloy. *Materials Research*. 2013; 16(1): 190-194.

[22] British Standard - BSEN. *10002-1*: Tensile testing of metallic materials. London: Macmillan; 1990. part 1.

[23] Salamci E. Ageing behaviour of spray cast Al-Zn-Mg-Cu alloys. *Turk Journal of Engineering and Environmental Science*. 2001; 25(6):681-686.

[24] Du ZW, Sun ZM, Shao BL, Zhou TT and Chen CQ. Quantitative evaluation of precipitates in an Al-Zn-Mg-Cu alloy after isotermal aging. *Materials Characerization*. 2006; 56:121-128.

[25] Fan X, Jiang D, Meng Q, Zhang B and Wang T. Evolution of eutectic structures in Al-Zn-Mg-Cu alloys during heat treatment. *Transactions of Nonferrous Metal Society of China*. 2006; 16:577-581.

[26] Guo H, Yang X and Zang M. Microstructure characteristics and mechanical properties of reoformed wrought aluminium alloy 2024. *Transactions of Nonferrous Metal Society of China*. 2008; 18:555-561.

[27] Kenji K, Tetsuro H, Tomoharu T and Zenji Horita. Fabrication and characterization of supersaturated Al-Mg alloys by severe plastic deformation and their mechanical properties. *Materials Transactions*. 2009; 50(1):76 to 81.

[28] Alexandre G, Tsutomu I, Xiaoyong Y, Yoshinobu M and Goroh I. Friction stir welding of a commercial 7075-T6 aluminium alloy: grain refinement, thermal stability and tensile properties. *Materials Transactions*. 2004; 45(8):2503-2508.

[29] Roberto BF and Terence GL. Using severe plastic deformation for the processing of advanced engineering materials. *Materials Transactions*. 2009; 50(7):1613-1619.

[30] Chen XH, Lu L and Lu K. Grain size dependence of tensile properties in ultrafine-grained Cu with nanoscale twins. *Scripta Materialia*. 2011; 64:311-314.

[31] Callister WD. *Materials science and engineering*: an introduction. 4th ed. New York: John Willey and Son Inc.; 1997.

[32] Demir H and Gündüz S. The effect of aging on machinability of 6061 aluminium alloy. *Material and Design*. 2009; 30:1480-1483.

[33] Kaya H, Uçar M, Cengiz A, Özyürek D, Çalis kan A and Ergün RE. The effect of aging on the machinability of AA7075 aluminium alloy. *Scientific Research and Essays*. 2012; 7(27):2424-30.

[34] Liao X Z, Zhao Y H and Zhu YT. Grain-size effect on the deformation mechanisms of nanostructured copper processed by high-pressure torsion. *Journal of Applied Physics*. 2004; 96(1):636-640.

[35] Zheng HW, Zhan YG, Chen Z, Lu C and Mai YW. Roles of grain boundary and dislocations at different deformation stages of nanocrystalline copper under tension. *Physics Letters A*. 2009; 373:570-574.

[36] Kumar R., Nicola L and Van der Giessen E. Density of grain boundaries and plasticity size effects: A discrete dislocation dynamics study. *Materials Science and Engineering A*. 2009; 527:7-15.

[37] Zhao YH, Liao XZ, Jin Z, Valiev RZ and Zhu YT. Microstructures and mechanical properties of ultrafine grained 7075 Al alloy processed by ECAP and their evolutions during annealing. *Acta Materialia*. 2004; 52:4589-99.

[38] Barsoum MW. *Fundamentals of Ceramics*. 1997, Pg. 99, McGraw-Hill, USA.