Effects of Alloying Elements on Mechanical Properties and Fracture Toughness of A7N01S-T5 Aluminum Alloy (Postprint)

Authors: Qin Chao, Gou Guoqing, Xiaoli Che, Chen Hui, Chen Jia

Date: 2023-03-18T00:00:00+00:00

Abstract

The mechanical properties and fracture toughness of four types of A7N01S-T5 aluminum alloys were tested to investigate the effects of different alloying elements. The results indicate that the suitable composition ratios of the three categories of alloying elements affecting the properties of A7N01S-T5 aluminum alloy are Zn(4.34), Mg(1.43), Mn(0.27), Cr(0.13), Zr(0.12), and Ti(0.066). Under these conditions, the tensile strength, yield strength, elongation, impact energy, and fracture toughness of the alloy are 415 MPa, 378 MPa, 13.49%, 12.3 J, and 28.950 $kJ \cdot m^{-2}$, respectively. Range analysis shows that Zn and Mg contents are the main influencing factors on both strength and ductility of the alloy. Therefore, to prepare alloys with excellent comprehensive properties, appropriate Zn and Mg contents must be selected. For alloys with suitable composition ratios, the intragranular precipitate phase ($MgZn_2$) exhibits a fine and dispersed distribution, while the intergranular precipitate phase ($MgZn_2$) is coarse and exhibits an intermittent distribution.

Full Text

Preamble

Vol. 29 No. 7
CHINESE JOURNAL OF MATERIALS RESEARCH
July 2015

Effect of Alloying Elements on Mechanical Properties and Fracture Toughness of A7N01S-T5 Aluminum Alloy

QIN Chao[1], GOU Guoqing[1], CHE Xiaoli[1], CHEN Hui[1], CHEN Jia[1],[2]

[1] School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu 610031, China
[2] Chengdu Technician College, Chengdu 611731, China

Supported by National Basic Research Program of China (No. 2014CB660807), National Science & Technology Pillar Program (No. 2015BAG12B01), and the Central University Basic Research Fund of China (No. 2682014CX003).

Manuscript received August 25, 2014; in revised form September 28, 2014.

Corresponding author: GOU Guoqing, Tel: (028)87600726, Email: gouguoqing@swjtu.cn

Abstract

The influence of alloying elements on the mechanical properties and fracture toughness of A7N01S-T5 aluminum alloy was investigated through tensile testing, impact testing, and three-point bending tests. The results demonstrate that with optimal composition ratios of the three categories of alloying elements—Zn (4.34 wt%), Mg (1.43 wt%), Mn (0.27 wt%), Cr (0.13 wt%), Zr (0.12 wt%), and Ti (0.066 wt%)—the A7N01S-T5 aluminum alloy achieves comprehensive performance characterized by tensile strength of 415 MPa, yield strength of 378 MPa, elongation of 13.49%, impact energy of 12.3 J, and fracture toughness of 28.950 $\mathrm{kJ \cdot m^{-2}}$. Range analysis reveals that Zn and Mg contents are the primary factors influencing both strength and ductility, and therefore must be carefully controlled. For alloys with appropriate composition ratios, the intragranular precipitate ´(MgZn$_2$) exhibits a fine, dispersed distribution, while the intergranular precipitate (MgZn$_2$) appears coarse and discontinuous.

Keywords: metallic materials, A7N01S-T5 aluminum alloy, alloying elements, microstructure, mechanical properties, fracture toughness

Introduction

The 7XXX series alloys, also known as super-hard aluminum alloys, include Al-Zn-Mg and Al-Zn-Mg-Cu systems. The A7N01S aluminum alloy belongs to the Al-Zn-Mg system and offers advantages such as low density and high strength, with capability for heat treatment strengthening. This alloy has been widely applied in China’ s high-speed train manufacturing sector [1,2]. A7N01 aluminum alloy profiles are primarily used for end beams, buffer structures, bases, thresholds, cross members, side frame skeletons, and bolster beams in high-speed train bodies. Its forgings are mainly employed for air spring brackets and reinforcement components at door corners, while plates are utilized for exterior panels, roof boards, and floor structures [3].

For high-speed train structural components requiring high damage tolerance, strength and fracture toughness represent two critically important performance indicators. As the principal alloying elements in 7XXX series aluminum alloys, Zn and Mg exert more pronounced effects on mechanical properties than other trace elements. Within certain ranges, increasing Zn and Mg contents leads to increased volume fraction of the metastable ´(MgZn$_2$) phase [4-6]. The high strength and significant hardening effects of 7XXX series aluminum alloys are primarily attributed to the ´ phase [7]; consequently, increasing Zn and Mg contents produces noticeable strengthening effects.

Nam and Lee [8] reported that 7XXX series aluminum alloys with Mn content of 0.7%-1.2% (mass fraction) can achieve substantially improved strength without sacrificing ductility, as Mn forms finely dispersed Al$_6$Mn precipitates. These Al$_6$Mn dispersoids provide precipitation strengthening, increase recrystallization temperature, and effectively refine recrystallized grains, thereby enhancing alloy strength. Cr exhibits similar grain-refining effects as Mn, forming highly stable Al$_7$Cr compounds that serve as heterogeneous nucleation sites during solidification, thus promoting nucleation and grain refinement [9]. Zr is a commonly used trace element in 7XXX series aluminum alloys. The combination of Zr and Al forms Al$_3$Zr intermetallic compounds that exist as dispersoids, refining the as-cast grain structure and inhibiting recrystallization during thermomechanical processing, which improves both strength and stress corrosion resistance [10-12]. Srivatsan et al. [13] found that grain refinement becomes more pronounced when Zr addition exceeds the peritectic composition.

China is currently developing higher-speed high-speed trains, imposing more stringent requirements on the comprehensive performance of body materials [14]. Therefore, optimizing the chemical composition of A7N01 aluminum alloy and thoroughly investigating its properties holds significant practical importance.

Experimental Methods

An $L_4(2^3)$ orthogonal design was employed to formulate three categories of alloying elements affecting A7N01S-T5 aluminum alloy performance: Zn-Mg content, Mn-Cr content, and Zr-Ti content. Four different 12 mm-thick A7N01S-T5 aluminum alloy profiles were prepared, designated as #1, #2, #3, and #4. The actual chemical compositions are listed in , with values in parentheses representing the designed composition ranges.

Following 12 months of natural aging after delivery, tensile test specimens were prepared along the L-direction according to GB/T 228.1-2010 "Metallic Materials—Tensile Testing—Part 1: Room Temperature Test Method." Testing was conducted on a WDW-3100 computer-controlled electronic universal testing machine at a crosshead speed of 2 mm/min. Standard V-notch impact specimens were prepared along the T-L direction following GB/T 229-2007 "Metallic Materials—Charpy Pendulum Impact Test Method," and tested using a JBN-300 pendulum impact tester.

Fracture toughness was evaluated via three-point bending tests on T-L oriented specimens with dimensions shown in [Figure 1: see original paper]. Fatigue pre-cracking was performed on a YK-1 tuning fork fatigue cracking machine, followed by fracture toughness testing on a WD-E precision microcomputer-controlled electronic universal testing machine with a span of 96 mm and loading rate of 0.5 mm/min. Fracture surfaces were examined using a JSM-6490LV scanning electron microscope (SEM). Metallographic specimens were prepared from the remaining fracture toughness test material, etched with Keller's reagent (1% HF + 1.5% HCl + 2.5% HNO_3 + 95% H_2O), and observed under a GX-40 optical microscope. Range analysis was subsequently performed on the experimental results to evaluate comprehensive performance and determine the optimal composition.

Experimental Results

Mechanical Properties and Fracture Toughness

The mechanical properties and fracture toughness of the four A7N01S-T5 aluminum alloy profiles with different compositions are summarized in . The #2 material exhibits the best fracture toughness and ductility but the lowest strength. Fracture toughness correlates with the yield-to-tensile ratio, showing an increasing trend as the yield-to-tensile ratio decreases. The #3 material possesses the highest tensile and yield strengths but the poorest fracture toughness, with Jm(12) of only 19.180 $\mathrm{kJ \cdot m^{-2}}$. Compared with the lowest-strength #2 material, the #3 material shows increases of 35 MPa in tensile strength and 42 MPa in yield strength.

The impact energies of the four materials follow the same trend as fracture toughness, with #2 material achieving the highest value of 16.13 J. [Figure 2: see original paper] presents the relationship between fracture toughness Jm(12) and impact energy KV_2 for the four materials, revealing a linear correlation between these parameters.

Range Analysis Results

Range analysis was performed on the orthogonal experimental results by calculating average mechanical properties and fracture toughness values for each factor and level, thereby determining target compositions and the sequence of influence. The range analysis results are presented in .

The data in indicate that Rm and $R_{0 \cdot 2}$ exhibit consistent trends, with alloy strength increasing with Zn-Mg content, decreasing with Mn-Cr content, and increasing with Zr-Ti content within the tested ranges. The variation in Zn-Mg content induces the most significant strength changes. Conversely, elongation (A), impact energy (KV_2), and fracture toughness Jm(12) show consistent decreasing trends with increasing Zn-Mg content, increasing trends with Mn-Cr content, and increasing trends with Zr-Ti content, with Zn-Mg content again producing the most pronounced effects.

Microstructural Analysis

The metallographic structures of the four A7N01S-T5 aluminum alloy profiles are shown in [Figure 3: see original paper]. The #1 material has completed recrystallization with relatively large grains and minimal retained fibrous structure [FIGURE:3(a)]. The #2 material features fine, flattened grains elongated along the rolling direction, with some regions retaining fibrous morphology [FIGURE:3(b)]. The #3 material shows the highest degree of recrystallization, with grain morphology and size similar to #1 but containing some abnormally grown grains [FIGURE:3(c)]. The #4 material exhibits recrystallized grains comparable in size to #1, with unrecrystallized regions retaining fibrous structure and some abnormally grown grains [FIGURE:3(d)].

SEM observations and compositional analysis of undissolved constituent particles are presented in [Figure 4: see original paper]. All four materials contain coarse second-phase particles (5-10 m) distributed within grains and along grain boundaries, predominantly at grain boundaries as short rod-like or irregular geometric shapes. EDS analysis (conducted at the square region in [FIGURE:4(b)]) reveals these particles contain Al, Zn, Mg, Fe, Mn, and Cr, identifying them as Fe-rich impurity phases such as $(FeMn)Al_6$ and Al(FeMnCr). Additionally, discontinuous spherical precipitates (<2 m) are observed at grain boundaries in all materials, most numerous and uniformly distributed in #1 and #2 (with #2 showing higher spheroidization), less abundant in #4, and least numerous with non-uniform distribution in #3. Continuous network precipitates appear at grain boundaries in #3 material and locally in #4 material. These discontinuous spherical and continuous network precipitates contain primarily Al, Zn, and Mg (analyzed at the cross marker in [FIGURE:4(c)]), identifying them as the strengthening phase ($MgZn_2$).

Fracture Morphology

[Figure 5: see original paper] shows the fracture morphologies of three-point bending specimens for the four A7N01S-T5 aluminum alloy profiles. The proportion of ductile to brittle fracture features on the fracture surfaces indicates the relative fracture toughness of each alloy. The #1 material exhibits primarily dimpled transgranular fracture with second-phase particles at dimple centers, some of which are fractured [FIGURE:5(a)]. The #2 material also shows dimpled transgranular fracture but with more numerous, larger, and deeper dimples containing smaller dimples within them [FIGURE:5(b)]. The #3 material displays a mixed morphology of quasi-cleavage and dimpled transgranular fracture, with transgranular fracture occupying a smaller proportion and showing secondary cracks and near-spherical second-phase particles on the fracture surface [FIGURE:5(c)]. The #4 material similarly exhibits mixed quasi-cleavage and dimpled transgranular fracture, but with a substantially higher proportion of dimpled transgranular fracture compared to #3, constituting the majority of the fracture surface [FIGURE:5(d)].

Discussion

Relationship Between Mechanical Properties and Fracture Toughness

The reduction in yield-to-tensile ratio R = $R_{0·2}$/Rm corresponds to increased yield-tensile difference (ΔR = Rm - $R_{0·2}$), which facilitates stress redistribution at stress concentration sites, retards or prevents brittle fracture, and improves material toughness. The essence of yield-to-tensile ratio R is the material' s capacity for strain hardening to increase strength to its peak value after reaching yield strength. Since cracks typically initiate after plastic deformation, higher fracture toughness indicates greater resistance to crack propagation. Therefore, fracture toughness can be analyzed by examining the yield-to-tensile ratio. A lower yield-to-tensile ratio and stronger strain hardening capacity indicate greater resistance to crack propagation and correspondingly higher fracture toughness.

Both fracture toughness and notched impact toughness represent material toughness indicators, and materials with high impact energy generally exhibit high fracture toughness. However, distinct differences exist between these parameters. First, their loading conditions differ: impact toughness measures the energy absorbed during instantaneous fracture under impact loading, whereas fracture toughness is measured under slow loading conditions. Second, the stress concentration levels differ due to variations in notch root radius, with impact specimens having significantly larger notch root radii. Finally, the processes reflected by these parameters differ: impact toughness characterizes the total energy consumption from elastic deformation through crack initiation to final fracture, while fracture toughness only reflects the process of unstable crack propagation.

Microstructural Effects on Strength and Fracture Toughness

The precipitation sequence of strengthening phases during aging of 7XXX series aluminum alloys is: α (supersaturated solid solution) → GP zones → ´ phase ($MgZn_2$) → phase ($MgZn_2$). Intragranular precipitates typically consist of GP zones and ´ phase, while intergranular precipitates are phase with accompanying precipitate-free zones at grain boundaries. GP zones are fully coherent with the matrix, ´ metastable phase is semi-coherent, and equilibrium phase is incoherent.

Alloy strength is primarily determined by the volume fraction, morphology, size, and distribution of intragranular ´ precipitates. More numerous, finer, and more dispersed precipitates produce more significant precipitation strengthening effects and higher alloy strength. As shown in [FIGURE:3(c)], the #3 material contains numerous ´ precipitates dispersed within the matrix, resulting in the highest strength. The #4 material [FIGURE:3(d)] has comparable ´ precipitate density to #3 but with non-uniform distribution, leading to reduced strength. Although the #1 material [FIGURE:3(a)] has lower ´ precipitate density than #4, its higher degree of dispersion results in essentially unchanged strength.

The #2 material [FIGURE:3(b)] exhibits the lowest strength due to fewer ´ precipitates and insufficient dispersion.

Alloy fracture toughness is closely related to intergranular precipitates. Continuous network distribution of phase is most detrimental to fracture toughness, whereas fine, discontinuous phase is beneficial, with smaller precipitate size and larger spacing yielding higher fracture toughness. One reason for the brittle fracture observed in #3 and #4 materials is the continuous network distribution of intergranular phase. [Figure 3: see original paper] also reveals significant differences in grain size among the four materials, which represents another intrinsic factor affecting fracture toughness. Grain boundaries are regions of disordered atomic arrangement with different orientations between adjacent grains. When plastic deformation transfers across a grain boundary into another grain, the boundary provides resistance to this transfer and the slip direction often changes after crossing. Consequently, this grain boundary-crossing, direction-changing deformation consumes more energy compared to intragranular deformation. During crack propagation, plastic deformation energy constitutes the main component of crack propagation resistance. Finer grains result in larger grain boundary area, and within a given region, greater energy is consumed during deformation and subsequent unstable crack propagation, leading to higher fracture toughness.

Therefore, the fracture toughness of the four materials is determined by the combined effects of intergranular precipitates and grain size. The #3 material exhibits coarse grains with continuous network phase distribution, resulting in the poorest fracture toughness. The #4 material shows partially coarse grains with locally distributed continuous network phase, yielding improved fracture toughness. The #1 material, despite having grain size comparable to #3, exhibits discontinuous phase distribution, further improving fracture toughness, indicating that intergranular precipitate distribution plays a dominant role. The #2 material features fine grains with precipitates even finer than those in #1, producing the most significant fracture toughness improvement.

The formation and distribution of these precipitates can be controlled through internal and external methods. Internally, Zn and Mg element contents can be controlled to reduce the volume fraction of intergranular precipitates at the source while meeting engineering strength requirements. Externally, aging treatment processes can be optimized, where low-temperature pre-aging and secondary aging produce small, discontinuous, spherical intergranular precipitates beneficial for fracture toughness. This occurs because lower atomic diffusion rates at low aging temperatures transport fewer atoms to grain boundaries, resulting in lower volume fractions of intergranular precipitates. However, excessively low temperatures excessively prolong the aging cycle.

Selection of Optimal Composition

Based on the orthogonal experimental range analysis results (), the various factors exhibit complex influences on mechanical properties and fracture toughness. For target parameters Rm and $R_{0\cdot 2}$, the composition yielding maximum values corresponds to #3 material, but this composition shows the poorest ductility, particularly in three-point bending fracture toughness tests where the fracture surface exhibits large-area brittle fracture with poor crack propagation resistance. Similarly, #2 material, which yields maximum values for target parameters A, KV_2, and Jm(12), exhibits low strength. Comparative analysis of the four materials indicates that #1 material demonstrates the best comprehensive performance, though its composition ratio has not yet reached the optimal level.

Conclusions

1. The optimal composition ratios for the three categories of alloying elements affecting A7N01S-T5 aluminum alloy performance are: Zn (4.34 wt%), Mg (1.43 wt%), Mn (0.27 wt%), Cr (0.13 wt%), Zr (0.12 wt%), and Ti (0.066 wt%). Under these conditions, the alloy achieves tensile strength of 415 MPa, yield strength of 378 MPa, elongation of 13.49%, impact energy of 12.3 J, and fracture toughness of 28.950 $\mathrm{kJ \cdot m^{-2}}$.
2. Zn and Mg contents are the primary factors influencing both alloy strength and ductility. Alloys with Zn content of 4.2%-4.5 wt% and Mg content of 1.2%-1.4 wt% exhibit optimal comprehensive performance.
3. The appropriate composition ratio results in fine, dispersed intragranular ´ precipitates and coarse, discontinuous intergranular precipitates, which accounts for the improved fracture toughness while maintaining high strength.

References

1. HUANG Ying, DENG Yunlai, CHEN Long, LIAO Fei, ZHANG Xinming. Microstructure, texture and property of extruded 7N01 aluminum alloy plates. *Chinese Journal of Materials Research*, 28(7), 541 (2014).
2. GOU Guoqing, HUANG Nan, CHEN Hui, MENG Lichun, WU Peipei. Research on stress corrosion behavior of A7N01S-T5 aluminum alloy for high speed train. *Materials Science and Technology*, 20(4), 1343 (2012).
3. LIU Jingan, XIE Shuisheng. *Application and Development of Aluminum Alloy* (Beijing, Metallurgy Industry Press, 2004) p.17.
4. P. C. Bai, X. H. Hou, X. Y. Zhang, C. W. Zhao, Y. M. Xing. Microstructure and mechanical properties of a large billet of spray formed Al-Zn-Mg-Cu alloy with high Zn content. *Materials Science and Engineering A*, 508, 23 (2009).

5. M. M. Sharma, M. F. Amateau, T. J. Eden. Aging response of Al-Zn-Mg-Cu spray formed alloys and their metal matrix composites. *Materials Science and Engineering A*, 424, 87 (2006).
6. LANG Yujing, CUI Hua, CAI Yuanhua, ZHANG Jishan. Dynamic precipitation behavior of 7050 aluminum alloy during deformation at different temperatures. *Chinese Journal of Materials Research*, 26(2), 143 (2012).
7. Z. B. He, Z. M. Yin, S. Lin, Y. Deng, B. C. Shang, X. A. Zhou. Preparation, microstructure and properties of Al-Zn-Mg-Sc alloy tubes. *Journal of Rare Earths*, 28(4), 641 (2010).
8. S. W. Nam, D. H. Lee. The effect of Mn on the mechanical behavior of Al alloys. *Metals and Materials*, 6(1), 13 (2000).
9. XU Lianghong, TIAN Zhiling, PENG Yun, ZHANG Xiaomu. Effects of trace elements on microstructure and mechanical properties of high strength aluminum alloy welds. *The Chinese Journal of Nonferrous Metals*, 18(6), 959 (2008).
10. A. Deschamps, Y. Brechet. Influence of quench and heating rates on the ageing response of an Al-Zn-Mg-(Zr) alloy. *Materials Science and Engineering A*, 251, 200 (1998).
11. W. J. Poole, D. J. Lloyd. The influence of chemistry and processing conditions on microstructures and mechanical properties of Al-Zn-Mg based alloys. *Nonferrous Metals Society of China*, 11(6), 822 (2001).
12. YANG Shoujie, XIE Youhua, ZHU Na, DAI Shenglong, LU Zheng, SU Bin, YAN Minggao. Effect of zirconium on the mechanical properties of a super-high strength aluminum alloy. *Chinese Journal of Materials Research*, 16(4), 406 (2002).
13. T. S. Srivatsan, M. Al-Hajri, M. Petraroli. Microstructure tensile deformation and fracture behaviour of aluminum alloy 7055. *Journal of Materials Science*, 32, 2883 (1997).
14. GOU Guoqing, HUANG Nan, CHEN Hui, LI Da, MENG Lichun. Research on corrosion behavior of welded joint of A7N01-T5 aluminum alloy for high-speed train. *Transactions of the China Welding Institution*, 32(10), 17 (2011).

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.