Dynamic mechanical response and weldability of high strength 7A62 aluminum alloy

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Abstract. The 7A62 as one kind of Al-Zn-Mg alloys is the highest strength weldable aluminum alloy currently. Plates and forgings of 7A62 alloy have been widely used in the defense system and main bearing parts of special vehicles. The microstructure, dynamic mechanical response and weldability of 7A62 aluminum alloy were investigated by OM, TEM, SHTB, DSC, microhardness and other tests. The morphology and mechanical test results showed that the 7A62 aluminum alloy strengthened by trans-scale precipitates had high strength, high hardness and good plastic toughness. The mechanical responses of the 7A62 aluminum alloy were found to be strain-rate sensitive and the dynamic response behavior was significantly higher than that of the 7A52 aluminum alloy through the SHTB test. In addition, for the as-welded 7A62 the tensile strength reached a scope of 260 MPa-305 MPa, which is considerably higher than the tensile properties reported when using ER5356. Because the weld of 7A62 alloy was free of macroscopic imperfections. The grains were highly equiaxied and homogeneous throughout the melting zone, showing smooth grain boundaries. Compared with 7A52, the lower melting point, low thermal enthalpy and low specific heat capacity of 7A62 alloy are more conducive to weld performed.

1. Introduction
Weldable aluminum alloy structure material is the key material of modern industrial development. In order to meet the requirements of lightweight design of key components in aerospace, transportation and other fields, new high performance weldable aluminum alloy structural materials must be used. The 7A62 aluminum alloy (7A62 alloy) is a new high strength weldable structural material, which has been independently developed in China, mainly contains Al, Zn and Mg, are refined by adding other transition elements (Mn, Cr, Zr, Ti). The Cu content is controlled in 7A62 alloy, and the strength of this alloy can reach more than 600 MPa by appropriate heat treatment process [1]. The 7A62 alloy with high specific strength, good weldability and corrosion resistance (including SCC resistance), as well as good thermal deformation performance and hardenability, is currently the highest strength weldable aluminum alloy, and has been applied in aerospace and vehicle fields.

Previous studies showed that the design of 7A62 alloy was based on the strengthening principle of high-density and cross-scale nanometer precipitation phase. And the aging precipitates maximization and high shear stress zone of equilibrium phase tangled with high density dislocation was formed by adjusting the total amount of Zn and Mg elements and the ratio of Zn to Mg [1]. The dynamic mechanical behavior and weldability were significantly affected by the microstructure, strengthening phase, melting point range, specific heat capacity and thermal expansion coefficient of aluminum
alloy[2,3]. 7A62 alloy is a new material integrating function and structure in vehicle fields. Its dynamic mechanical behavior and weldability are worthy of attention. The dynamic mechanical response and weldability of 7A62 alloy were investigated by analyzing its microstructure and physical properties in this paper.

2. Experimental procedure

Experimental materials are commercially produced 7A62 and 7A52 alloy plates with the thickness of 25mm, and the materials are in the T6 state of the quenching and artificial aging. Their chemical compositions are shown in table 1.

| Alloy | Si  | Fe  | Cu  | Mg  | Zn  | Mn  | Cr  | Zr  | Ti  | Be  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 7A62  | 0.029 | 0.076 | 0.338 | 2.75 | 6.76 | 0.324 | 0.131 | 0.099 | 0.038 | 0.0015 |
| 7A52  | 0.046 | 0.138 | 0.127 | 2.18 | 4.08 | 0.209 | 0.163 | 0.083 | 0.109 | —   |

All samples of 7A62 alloy were cut perpendicular to the rolling direction of the alloy plate. The tensile tests for cylindrical specimens of the alloy and plate specimens of full thickness of weld were carried out on a CMT-4105 test machine according to GB/T 228.1-2010, with a nominal strain rate of 10\(^{-3}\) s\(^{-1}\). Brinell hardness test was completed using 320HBS-3000 test machine. The notched impact test was completed according to GB/T 229-2007. The fracture toughness test was conducted using Instron 8801-100N test machine according to GB/T 21143-2007.

Microstructure of 7A62 alloy and weld was observed by optical microscopy (OM-LEICA MEF4M), and the morphology and distribution of the strengthened phase of 7A62 alloy were further observed by transmission electron microscopy (TEM-FEI TECNAI G2). Specimens for OM observation were prepared by standard metallographic procedures using Keller’s reagent. The thin foils for TEM observation were prepared by twinjet electro-polishing in the solution of 70% methanol and 30% nitric acid at -20°C.

In order to determine the mechanical response of 7A62 alloy, a comparative test was designed to probe the strain hardening behavior as well as the strain rate and temperature sensitivities of 7A62 alloy and 7A52 alloy. The dynamic strain rate tests were conducted using a Split Hopkinson Tensile Bar (SHTB) with strain rates from 10\(^{3}\) s\(^{-1}\) to 10\(^{5}\) s\(^{-1}\). To determine the temperature dependence of the mechanical response of both alloys, the dynamic tests were performed at temperatures ranging from 25 to 500°C with strain rates of 10\(^{3}\) s\(^{-1}\). Differential scanning calorimetry (DSC) analyses were conducted using a SDT-Q600 differential scanning calorimeter to decide the melt temperature and specific heat capacity at a constant heating rate of 10°C/min from 25°C to 700°C and the standard sample was pure Al. The welding wire of 7A62 alloy was RE5356, and the microhardness of the weld was tested on MH-50D test machine.

3. Results

3.1. Mechanical properties

Mechanical properties of 7A62 alloy depend on its chemical composition and structure. The mechanical properties at room temperature of transverse plates with T6 peak aging, such as tensile properties, brinell hardness, impact energy and fracture toughness, are shown in table 2. It can be seen that the strength of the alloy can reach above 600 MPa and the brinell hardness HB exceeds 160. The strength of the alloy mainly depends on the strengthening phase [1]. The impact fracture and ductile fracture values are relatively high, which depends on the grain boundary precipitates [4] and the size and distribution of coarse compounds [5]. The static mechanical properties of the alloy reflect the dynamic mechanical behavior to some extent.
3.2. Microstructure

Figure 1 shows the optical morphology of 7A62 alloy in T6 state. As shown in figure 1, the matrix microstructure is relatively uniform. The elongated grains are distributed along the deformation direction, while a small number of coarse phase particles with a size less than 10 μm are dispersed in the matrix. These coarse phase particles are the compounds which are made up of the Mn, Ti, Fe, Si and other elements by matrix segregation. Different from the coarse compounds of Mn, Ti and Fe soluble in Al-Cr in 7A52 aluminum alloy [6,7].

![Figure 1. Optical morphology of 7A62 aluminum alloy in T6 aging.](image)

| Alloy     | R_m (MPa) | R_p0.2 (MPa) | A (%) | HBW | KU2 (J) | Kc (MPa·m^{1/2}) |
|-----------|-----------|--------------|-------|-----|---------|-------------------|
| 7A62-T6   | 615~646   | 559~602      | 8.5~13.5 | 170 | 13.5    | 23                |

3.3. Dynamic mechanical response

Figure 3(a) shows the true stress-strain curve of 7A62 alloy under strain rate jump tests. Maximal strain rate sensitivity of 7A62 alloy is observed, and the yield strength of the alloy varies from 650 MPa to 760 MPa in the strain rate range of 10^{-3}-10^3 s^{-1}. When the strain rate was about 1500 s^{-1}, the yield strength of the alloy is increased about 150 MPa compared with the quasi-static condition. Figure 3 (b) shows the true stress-strain curve of 7A52 alloy under strain rate jump tests. It can be seen that
7A52 alloy is sensitive to the strain rate, and the yield strength of the material varies from 450 MPa to 610 MPa in the strain rate range of $10^{-3}$-$10^{3}$ s$^{-1}$. When the strain rate was about 1750 s$^{-1}$, the yield strength of the alloy was about 150 MPa higher than that of the quasi-static state. Figure 3(a) and figure 3(b) show that 7A62 alloy is more sensitive to strain rate than 7A52, and the plasticity of 7A52 alloy is better than 7A62.

![Figure 2](image)

**Figure 2.** TEM image of nano-precipitated phases of the matrix in 7A62 alloy after T6 temper, (a) precipitated phase, (b) equilibrium phase.

![Figure 3](image)

**Figure 3.** True stress-strain curves of the tensile tests performed at a range of strain rates, (a) 7A62 alloy, (b) 7A52 alloy.

Figure 4 shows the true stress-strain curves at 25 °C, 200 °C, 300 °C, 400 °C and 500 °C. The strain rate of 7A62 alloy is about 1100 s$^{-1}$, and that of 7A52 alloy is about 1200 s$^{-1}$. The yield strengths of both alloy decreased with the increase of temperature are shown in figure 4. Examination of dynamic strain rate tests (figure 4), reveals that there is some softening at 200 °C for 7A62 alloy and very minimally for 7A52. The strength of 7A62 alloy is higher than that of 7A52 alloy at 25 °C ~ 400 °C, but the strength of 7A62 alloy is lower than that of 7A52 alloy at 500 °C because of different strain rate. The Johnson-Cook dynamic constitutive equation is constructed [8], the temperature coefficient of 7A62 alloy $m=1.98$, and that of 7A52 alloy $m=2.57$. The results show that the yield strength of 7A52 alloy is slightly more sensitive to temperature than that of 7A62 alloy under the same strain rate, and the high-temperature performance of 7A62 alloy is better than that of 7A52, but the strength of 7A52 alloy at 500 °C is slightly higher than that of 7A62 alloy due to the effect of strain rate.
3.4. Weldability

DSC curves of T6 aged 7A62 and 7A52 alloys are shown in figure 5. The peak temperature of a given reaction is dependent on the alloy melting or solidification under the same condition. The area under a given DSC peak is calculated qualitatively by the enthalpy value of the alloy melting or solidification. Figure 5 (a) shows that the melting peak temperature T and enthalpy H of 7A52 alloy are higher than that of 7A62 alloy during the heating process. Figure 5 (b) shows that the solidification peak temperature T and enthalpy H of 7A52 alloy in the cooling process are higher than that of 7A62 alloy. DSC results showed that the specific heat capacity of 7A52 alloy at room temperature was 1.01 J/g·K, and that of 7A62 alloy at room temperature was 0.88 J/g·K. These show that the melting temperature range, endothermic enthalpy, exothermic enthalpy and specific heat capacity of 7A62 alloy are lower than that of 7A52 alloy, which is more favorable to the welding performance of the 7A62 alloy.

Using ER5356 filler wire and gas metal arc welding (GMAW) process, the welding joint strength of 7A62 alloy is up to 260 MPa ~ 305 MPa. Figure 6 shows the distribution of microhardness in the weld of 7A62 alloy. The range of weld hardness test is shown in the dotted line inset in figure 6. The highest microhardness value was measured on 7A62 base metal, followed by the heat-affected zone (HAZ) and the weld metal. Microhardness decreased in the HAZ because of the effect of the heat during the welding process. The reduction in hardness could have resulted from recrystallization or grain growth [9]. The microhardness of 7A62 base metal at the fusion line is the lowest 105 HV, and
the width of the heat-affected zone is only about 9 mm. The microhardness value continued to decrease when entering the weld metal. From the edge of the weld to the center of the weld, the hardness value steadily changed around 75 HV. The microhardness distribution indicates that the lowest microhardness and the weakest joint appear in the weld metal. However, the microhardness value of the pores zone at the joint of each pass is 65HV. Therefore, it is necessary to control the welding parameters and eliminate the defects of the weld pores at the joint of each weld line, so as to further improve the strength of the weld of 7A62 alloy thick plate.

**Figure 6.** Microhardness distribution of 7A62 alloy weld, inset corresponding the range of microhardness.

Figure 7 shows the metallographic microstructure of 7A62 alloy and the weld metal. The microstructure of the heat-affected zone, the fusion zone and the weld zone can be seen in figure 7(a). The microstructure of the 7A62 base metal and the ER5356 filler are well fused. The microstructure of 7A62 base metal in the heat-affected zone near the fusion line is composed of deformed grains and few equiaxed grains. It indicates that recrystallization has occurred in very few tissues. As shown in figure 7(b), the fusion zone is a fine dendritic structure, and the size of dendritic grains in the weld zone is increased significantly due to different cooling rates. The fine dendritic microstructure can increase the strength of the weld fusion zone and further indicate that the strength and hardness of the weld zone are the lowest.

**Figure 7.** Optical morphology of 7A62 alloy and the weld metal.

4. **Discussion**

4.1. Effects of composition and microstructure on dynamic behavior
The chemical composition of 7A62 alloy is mainly Zn and Mg, and the total amount of Zn and Mg elements is about 9.5% (wt%), and Zn/Mg is about 2.45. The total amount of strengthening phase \( \eta' \) and T of 7A62 alloy is about 9.5% (wt%), and is higher than that of strengthening phase \( \eta' \) and T of 7A52 alloy about 6.5% (wt%) [1]. The dynamic strength of 7A62 alloy is higher than that of 7A52 because of the numerous strengthening precipitates in the matrix of 7A62 alloy. But the dynamic plasticity of 7A62 alloy is slightly lower than that of 7A52 due to the high density of the strengthening phase and the coarse compounds. Under different strain rates at room temperature, the strengthening phase of 7A62 alloy showed a trend of local density and the density was higher than that of 7A52, which made the sensitivity of dynamic strain rate of 7A62 alloy higher than that of 7A52. However, with the increase of temperature, especially at 500°C during the dynamic deformation process, the resolution of the strengthening precipitates is obvious, so that the dynamic response behavior of 7A62 and 7A52 alloys is the same.

4.2. Effects of composition and physical properties on weldability

The components of 7A62 alloy include main alloy elements Zn, Mg and transition elements Mn, Cr, Zr, Ti, Cu and impurity elements Fe and Si. The strength of 7A62 alloy increases with the increase of Zn content. However, when the Zn content exceeds 7.5%, the welding performance of the alloy begins to deteriorate, and the hot crack tendency and porosity of the weld increase. The reason is that the hydrogen absorption of 7A62 alloy with high Zn is increased when it is cast. The weld crack tendency of the alloy decreases with the increase of Mg content. When Zn/Mg is 2.5, the main strengthening phase is MgZn\(_2\) [10]. The nanoscale equilibrium phase is formed in 7A62 alloy due to Mn [1], which plays a supplementary strengthening role, improves the resistance to stress corrosion, inhibits the formation of recrystallization structure in the weld thermal affected zone (see figure 7a), and reduces the softening effect of the weld thermal affected zone. Cr, Zr and Ti are all microalloyed elements in 7A62 alloy, which play a role of precipitation strengthening, and mainly refine the as-cast structure of the weld and improve the ability to resist weld cracks. Cu can increase the dispersion of the precipitated phase, and improve the grain boundary structure in 7A62 alloy. However, when the Cu content goes up, the welding performance is damaged, and the hot crack tendency of the welding joint is serious during solidification. Therefore, for 7A62 alloy, adding a small amount of Cu is beneficial to the welding performance and intergranular corrosion performance.

The physical properties of 7A62 aluminum alloy, such as melting point range, enthalpy value and specific heat capacity at room temperature, are lower than that of 7A52 aluminum alloy, which is more beneficial to the melting and solidification of the matrix during the welding process, and can reduce the effect of heat input on the softening and solidification heat crack formation at the welding joint. However, in the actual production process, the hydrogen absorption of high alloyed 7A62 alloy is more serious than that of 7A52, and the heat input of MIG welding process is slightly higher than that of 7A52, which is conducive to bubble escape and weld quality improvement.

5. Conclusions

(1) There are numerous trans-nanoscale particles of strengthening phase of \( \eta' \) and T in 7A62-T6 alloy, which makes the alloy more than 600 MPa in strength, with high hardness and good plastic toughness.

(2) A large number of high-density trans-scale precipitates in 7A62 alloy make the strength of 7A62 alloy more sensitive to strain rate and less sensitive to temperature than 7A52.

(3) The weld of 7A62 base metal and ER5356 filler is a fine dendritic microstructure with small heat affected zone. 7A62 alloy has high welding performance, and the strength of weld can reach 260 MPa-305 MPa.

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