Enhancement of strength mechanical and corrosion resistance of 7055 alloy with minor Sc and Y addition

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Abstract
A new type of 7055-Y-Sc alloy with high strength and corrosion resistance was prepared. Eutectic Al3Y particles with sizes in the range of 500–600 nm were found in the as-cast structure of the 7055-Y-Sc alloys. The addition of Y significantly accelerated the precipitation of Al3Zr with L12 structure in Al–Zr–Y alloy, and the number density of Al3 (Zr, Y) precipitates was almost a grade higher than that of Al3Zr. In the process of aging at 120 °C/12 h, the nano scale L12-type Al3 (Sc, Ys) phase nucleated uniformly within the Al matrix and nonuniformly on the dislocation. The grain size decreased from 100–200 um in 7055-Y-0.25Sc to 40–50 um in 7055-Y-0.25Sc, the percentage of Sc continued to increase, and the grain size remained unchanged or even increased, thereby decreasing the Vickers hardness of 7055-Y-Sc alloys from 196.4 HV to 187.9 HV. After aging, the hardness and tensile properties of 7055-Y-Sc alloy showed good performance. The effective Sc proportion of the 7055-Y-Sc alloy was 0.25%. Its tensile strength was 398.6 MPa. Its conductivity was 33.8% IACS. The current corrosion density was 6.7 × 10−3 A cm−2, its good strength, corrosion resistance and conductivity make the studied alloy to be a promising material.

1. Introduction

The demand for lightweight structural materials in household appliances, automobile and other industries has led to extensive study on aluminium alloys in recent years. The development of some aluminium alloys has been successfully applied commercially [1–7]. In aerospace and automotive fields, materials need to have low density, high strength and good corrosion resistance. Al–Zn–Mg–Cu series (7xxx) alloys have become the focus of research in the field of modern aerospace [8–14]. With the development of aerospace industry, the use of aluminium alloy has become widespread, but strict requirements are in place regarding the strength, corrosion resistance and electrical conductivity of the aluminium alloy.

Scandium is the most effective strengthening additive in as-cast Al alloy. In recent years, the research on the microstructure and mechanical properties of 7xxx alloy containing Sc and Zr has attracted widespread attention. The engineering application of aluminium alloy is mostly concentrated on the ultra-high-strength 7xxx alloy (Al–Zn–Mg–Cu). The effect of rare earth elements on the microstructure and mechanical properties of 7xxx alloy has been studied in a large number of researches, it has been found that adding microscale Sc can ameliorate the microstructure of Al alloy and improve its mechanical properties [15]. After Sc-modification, the non-recrystallization structure is preserved in the high temperature range due to formation of Al3Sc nanosized precipitates. The element of Zr improves the thermal stability of the alloy by forming Al3 (Sc, Zr) dispersion. Al–Zr–Sc alloy is the most commonly used aluminium alloy material that has high strength and good thermal...
stability \cite{16–20}. Yttrium plays the same role in Al–Zn–Mg–Cu–Zr alloy, yttrium significantly accelerates the precipitation kinetics, resulting to improvement of thermal stability in Y-doped alloy and elimination of negative effects owing to Fe and Si impurities. The recrystallization temperature of Al\(_3\) (Zr, Y) dispersion is increased, and the coarsening resistance is higher than that of Al\(_3\)Zr \cite{21, 22}.

This study aimed to develop a 7055 alloy with the compound addition of Sc and Y, which improve the alloy’s strength, conductivity and service life.

2. Material and methods

7055-Y-Sc alloys were melted in a resistance furnace from pure Al (99.99%), Al-2Sc and Al-10Y master alloys. The melting temperature of the 7055 alloy was controlled at 720 °C–740 °C. Alloy ingots with the following dimensions were prepared: width of 50 mm, thickness of 30 mm and height of 120 mm. Samples were collected from the lower part of the water-cooled copper mould. The chemical compositions of these five alloys are shown in table 1. After homogenisation treatment at 465 °C/24 h and solid solution treatment at 455 °C/2 h, the sheet was finally aged at 120 °C/12 h.

The microstructures of the alloys were observed by x-Ray Diffraction (XRD), optical microscopy (OM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Before TEM analysis, grinded the sample to a thickness of 50 um and then thinned it by the electrolytic double spray device. Transmission electron microscopy (TEM; JEM 2100) was used to study the structure of the films at 200 kV. Samples were prepared using A2 electrolyte on the Struers Tenupol-5 device. Hardness was measured by Vickers microhardness test. The polarisation curves of the 7055-0.25Y-xSc alloy were measured by PS-268A

\begin{table}
\centering
\caption{Chemical composition of the 7055-Y-xSc alloys.}
\label{tab:1}
\begin{tabular}{cccccc}
\hline
 & Zn & Mg & Cu & Zr & Y & Sc \\
\hline
7055-Y-0Sc & 7.7\% & 1.95\% & 2.1\% & 0.16\% & 0.25\% & 0\% \\
7055-Y-0.2Sc & 7.7\% & 1.95\% & 2.1\% & 0.16\% & 0.25\% & 0.2\% \\
7055-Y-0.25Sc & 7.7\% & 1.95\% & 2.1\% & 0.16\% & 0.25\% & 0.25\% \\
7055-Y-0.3Sc & 7.7\% & 1.95\% & 2.1\% & 0.16\% & 0.25\% & 0.3\% \\
7055-Y-0.35Sc & 7.7\% & 1.95\% & 2.1\% & 0.16\% & 0.25\% & 0.35\% \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{SEM images of as-cast alloys (a) Al-Y-0Sc, (b) Al-Y-0.2Sc, (c) Al-Y-0.25Sc, (d) Al-Y-0.3Sc, (e) Al-Y-0.35Sc.}
\end{figure}
Figure 2. OM micrographs of alloys after aging (a) Al-Y-0Sc, (b) Al-Y-0.2Sc c, (c) Al-Y-0.25Sc, (d) Al-Y-0.3Sc, (e) Al-Y-0.35Sc.

Figure 3. Energy spectrum of Al-Y-0.25Sc alloy; (a) as cast alloy, (b) aged alloy.

Figure 4. XRD-patterns of the as cast Al–Y–Sc alloys, (a): Al-Y-0Sc; (b): Al-Y-0.25Sc; (c): Al-Y-0.25Sc; (d): Al-Y-0.35Sc; (e): Al-Y-0.35Sc.
electrochemical measuring instrument. The reference electrode was saturated calomel electrode. The auxiliary electrode was platinum plate. The environment was NaCl solution at 3.5% mass concentration.

3. Results and discussion

The as-cast structures were composed of dendrite Al-based solid solution and non-equilibrium eutectic structure between dendrites, as shown in figure 1 and figure 2. An obvious dendrite segregation was observed in the as-cast structure, a large amount of Cu segregation occurs at grain boundaries. From the perspective of matrix grain size, the average grain size was about 40–50 μm, when Sc content up to 0.25%, the effect of grain refinement was effective, and the grain size was more uniform, moreover, the secondary dendrite spacing was reduced [23–25]. When the amount of addition exceeded 0.30%, the effect of grain refinement was not observed.

Aluminium solid solution and Y-rich phases were formation in the as-cast state in the investigated alloys. The EDS analysis in figure 3 and table 2 show that the round white phase is rich in Al and Y, finally, it is confirmed that this particle is Al3Y [26, 27]. Al3Y phase particles were located on the grain boundaries and formed a circular-shaped eutectic structure at the grain boundary of dendritic cells. The size of the Al3Y particles was approximately 100–200 nm. During the homogenisation of 7055-Y-Sc alloy at 465 °C for 24 h, yttrium was uniformly distributed in aluminum solid solution, and at the same time, part of the Al3Y phase dissolved in the

| Table 2. EDS elemental compositions of different positions of alloy. |
|--------------------------|----------|-------|------|--------|
|                          | Al (at%) | Cu (at%) | Y (at%) | Sc (at%) |
| 1                        | 84.43    | 12.48   | 2.97   | 0       |
| 2                        | 88.02    | 10.42   | 0.61   | 0.52    |

Figure 5. TEM topographic images of Al-Y-0.25Sc alloy after aging.
solid solution of aluminium, some Y atoms diffuse and combine with Zr atoms to form metastable Al3(Y, Zr) phase [23, 24, 28]. Under certain cooling conditions, the melting of the 7055-Y-Sc alloy preferentially formed the metastable Al3Zr particles. Al3Zr particles precipitated the nucleated particles into the aluminium matrix and was distributed uniformly on the dislocation, Sc atoms diffuse to Al3Zr phase and replace the part Zr atoms form Al3(Sc, Zr) phase. Al3(Sc, Zr) phase dispersions were usually homogeneous [28, 29]. The precipitation phase of L12 was Al3(Sc, Y) at homogenisation treatment stage, with the subsequent solution and aging treatment, L12 Al3(Sc, Y) phase remained until after aging treatment.

The Al–Y–Sc alloys were analyzed by XRD to determine the phase composition of the alloy. As shown in the figure 4, the main phase group of the alloy were α-Al and MgZn2. Some other elements were not shown in the test due to their low content, for example the rare earth elements Sc and Y. Tem images of the 7055-Y-0.25Sc alloy were presented in figure 5. L12 particles nucleated and precipitated homogeneously in aluminum matrix, heterogeneous precipitation on the dislocations [25, 30]. Al3Sc dispersed phase was typical homogeneous nucleation, the L12 precipitates formed in the investigated alloy was Al3(Sc, Y) phase. After aging at 120 °C for 12 h, the average size of L12 precipitates in 7055-Y-0.25Sc alloy was about 15 nm. There are fine precipitates in the grain of 7055-0.2Sc alloy, in addition, high density Al3(Sc, Y) particles were observed in the samples, some of which were located at dislocation positions near GBs (grain boundary) [31, 32]. The precipitates first precipitated and grew at GBs, and then transform into stable phase by absorbing solute atoms around the particles.

As showed from the figure 6, the hardness values for 7055-Y-0Sc alloy was 190.2 HV, after adding 0.2% and 0.25%Sc, the hardness increased to 192.6 and 196.4 HV, respectively. When the Sc content was added to 0.3% and 0.35%, the hardness of 7055-Y-0.4Sc decreased to 195.2 and 187.9 HV, respectively. 100–200 nm in size of the Al3Y particles contributed more to the hardness of the material than the dissolved Yttrium in the aluminium solid solution. After adding Sc, the hardness of 7055-Y-Sc alloys increased initially and then decreased when Sc content exceeded 0.25%. From the perspective of distribution, the Y-containing phase was mainly distributed at the grain boundary, which allowed component supercooling and grain growth inhibition, thereby refining the grain. The increase of Sc content led to the homogeneous nucleation of Al3(Sc, Y) that was precipitated from L12 in the aluminium matrix [23, 26, 33], the dislocation was not uniform in the aging process, as a result, the hardness decreased.

The electrical conductivity values of the investigated alloys were presented in figure 6. The electrical conductivity of 7055-Y-Sc alloys generally increased. The electrical conductivity of 7055-Y-0Sc alloy was 30.2% IACS, and the conductivity began to increase after the addition of Sc. When the Sc content reached 0.25%, the conductivity of 7055-Y-0.25Sc alloy fluctuated slightly. Then, with increasing Sc content, the electrical conductivity of the sample continued to rise. The highest electrical conductivity of 33.8% IACS was achieved when the Sc content increased to 0.35%. The microstructure of the 7055-Y-Sc alloy was composed of the α-Al matrix and a small amount of η′ phase, and the number and distribution of these precipitates affected the conductivity of 7055-Y-Sc alloys [34]. With increasing Sc content, the electrical conductivity of the aged 7055-Y-Sc alloys increased. After aging treatment at 120 °C/12 h, the solute atoms were continuously precipitated, leading to the consumption of the solute atoms on the grain boundary, further increasing the number of poor solute atoms on the grain boundary, weakening the scattering effect on electrons and further improving the electrical conductivity of the alloy [4, 35, 36].
Table 3. Tensile properties of the 7055–Y-Sc alloys.

| Alloys     | UTS (MPa) | EL (%) |
|------------|-----------|--------|
| 7055-Y-0Sc | 233.1     | 7      |
| 7055-Y-0.2Sc | 246.8    | 6.8    |
| 7055-Y-0.25Sc | 398.6    | 15.1   |
| 7055-Y-0.3Sc | 353.9    | 13.2   |
| 7055-Y-0.35Sc | 316.0    | 9.8    |

Table 3 and figure 7. were presented the tensile test results and typical tensile stress-strain curves. The ultimate tensile strength (UTS) value was 233.1 MPa in the as-deformed state of the 7055–Y-0Sc, compared with the 7055–Y-0Sc samples, the tensile strength of the 7055–Y-0.2Sc samples ascended little, and the elongation decreased, which may be due to the fact that the residual Al2CuMg phase compound in the homogenised structure cannot completely dissolve into the matrix after the solution treatment. The compound itself has low fracture strength and high brittleness, which are extremely detrimental to the plasticity of the alloy. Thus, the elongation of the alloy was reduced. 7055–Y-0.25 alloy has high strength and elongation due to high Sc content and high proportion of L12 precipitation, the tensile strength of the 7055–Y-Sc alloy was achieved 398.6 MPa and...
the elongation was 15.1%. Subsequent Al3(Scx Yy) phases effectively refined the grains. 7055-Y-0.25Sc alloy tensile properties were greatly improved due to dislocation and grain boundaries were fixed by L12 precipitates and eutectic Al3Y phase particles, the Nano-precipitates lead to the accumulation of dislocations in the aluminum alloy during the stretching process, thus increasing the ultimate tensile strength and improving the elongation of the 7055-Y-Sc alloys [23, 26, 37, 38].

Figure 8 and table 4 indicated the typical potential polarization curve of 7055-Y-Sc alloys with different Sc contents in 3.5% NaCl solution. The electrochemical corrosion rate is proportional to the current corrosion density, while the current corrosion density of 7055 alloy decreases with the increase of the proportion of Sc. For the 7055 alloy, both the θ-CuAl2 and precipitation-free zone phases on the grain boundary (GB) may be used as the anode phase compared with the Al matrix in the corrosion environment, and both of them can be dissolved preferentially. However, the tendency of the θ-CuAl2 phase as the anode was more serious and caused the corrosion to expand along the GBs. Therefore, the corrosion performance of the alloy was determined by the size and distribution of the precipitates at the GBs [11, 33, 39]. Al3(Scx Yy) particles were precipitated in 7055 alloys with Sc content, which was very close to the crystal structure and the lattice constant of Al-matrix. In consequence, the particles had an excellent grain refining effect, making the alloy structure more uniform and finer. Such effect can prevent the subcrystal structure and the movement of dislocation, as well as inhibit the precipitation and aggregation of θ-CuAl2 phase at the GBs, and greatly reducing the corrosion sensitivity of the 7055-Y-Sc alloy [38, 39]. The grain size of 7055-Y-0.25Sc alloy sample was the smallest, thus, its corrosion resistance was the best.

### 4. Conclusions

1. The reason for the 7055-Y-Sc alloys grain refinement is the formation of nano-sized Al3(Scx Yy) phase.

2. After the aging treatment at 120 °C for 12 h, the Vickers hardness of the 7055-Y-0.25Sc alloy was highest, and this promotion was due to the contribution of 500–600 nm Al3Y phase and the L12 precipitates of the Al3(Scx Yy) phase. The 7055-Y-0.25Sc alloy had enough Al3(Scx Yy) phase particles and the smallest grain size. Thus, the hardness was increased the most.

3. The addition of Sc improves the strength and ductility of 7055-Y-Sc alloys after aging. This phenomenon was mainly due to the grain refinement, the grain size is finer, the density is higher and the grain is more uniform in the 7055-Y-0.25Sc alloy.

4. The electrical conductivity and corrosion resistance of the 7055-Y-Sc alloy increased with the increase of Sc content. Al3(Scx Yy) particles had an excellent grain refining effect, more of this particle can prevent the subcrystal structure and the movement of dislocation, and greatly reducing the corrosion sensitivity of the 7055-Y-Sc alloy.

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### Conflicts of interest

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this paper.

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**Table 4. Electrochemical character of 7055-xSc alloy.**

| 7055-Y-xSc | Ecorr(V) | Icorr(A/cm²) |
|-----------|---------|-------------|
| 7055-Y-0Sc | −0.798  | 3.98 × 10⁻⁶ |
| 7055-Y-0.2Sc | −0.784  | 3.13 × 10⁻⁶ |
| 7055-Y-0.25Sc | −0.727  | 1.40 × 10⁻⁷ |
| 7055-Y-0.3Sc | −0.720  | 8.50 × 10⁻⁷ |
| 7055-Y-0.35Sc | −0.740  | 6.70 × 10⁻⁸ |
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