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Effect of Sc and Nd on the Microstructure and Mechanical Properties of Al-Mg-Mn Alloy

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The effects of micro-alloying with small amounts of Sc and Nd elements on the microstructure and mechanical properties of Al-Mg-Mn alloy were systematically investigated. The results show that the grains of Al-Mg-Mn alloy can be refined by the addition of minor Sc and Nd. Adding 0.2 wt.% Sc or 0.2 wt.% Nd element to Al-Mg-Mn alloy can improve the strength and recrystallization temperature. Especially, after a combined addition of 0.1 wt.% Sc and 0.1 wt.% Nd, owing to the $Al_{16}Mg_7Nd$ phase formed in the alloy, which pinned at the grain boundary can hinder the migration of the grain boundary during annealing process, the recrystallization temperature of the Al-Mg-Mn alloy is increased by 100 °C, and the increments of tensile strength and yield strength are 65 and 55 MPa, respectively.

Keywords Al-Mg-Mn alloy, mechanical properties, microstructure, Nd, Sc

1. Introduction

Although the Al-Mg-Mn alloys have good formability, they have a relatively low strength with a tendency of Luders band formation (Ref 1, 2), which restricts their use to interior structural applications (Ref 3). Recently, some reports about the addition of minor element to enhance the strength of the Al-Mg-Mn alloys are proposed. Zhu and Starink (Ref 4) reported that the proof strengths of the aged Al-Mg-Mn alloys with up to 0.4 wt.% Cu range from 130 to 370 MPa. Ning et al. (Ref 5) stated that the addition of Zr to Al-4.58%Mg-0.56%Mn-0.08Cr (in wt.%) (5083Al) effectively enhanced the strength of the 5083Al alloy after both hot extrusion and hot ECAP (equal-channel angular pressing). The Al-Mg-Mn alloy containing rare eath (RE) element is one of the most promising materials for the aerospace applications due to its high strength, good corrosion resistance, weldability, and fatigue fracture resistance (Ref 6, 7). It has been shown that a significant increase in the strength of Al-Mg alloys can be obtained by the addition of a small amount of scandium (Sc) (Ref 8-11), due to the existence of coherent and finely dispersed L12 Al_3Sc precipitates (Ref 9). However, owing to the high price of Sc and Sc-containing aluminum alloys, the research and application of these alloys have been severely retarded. Thus, a key to develop the Al-Mg alloys containing Sc is to reduce the content of Sc additions. Micro-alloying with other elements substituting for Sc is considered as an effective way of both enhancing the properties (Ref 12) and lowering the cost of the alloys (the cost of Al-Sc is about four times higher than the cost of Al-Nd in the same content of Sc or Nd according to the market survey). In our study, RE element Nd was chosen due to its similar properties and crystallography parameters with Sc. The effects of Sc and Nd on the mechanical properties and microstructure of Al-Mg-Mn alloys were systematically studied.

2. Experimental Procedure

The experimental alloys were prepared through a conventional melting and casting route. Commercial pure aluminum and magnesium, as-cast Al-10 wt.% Mn, Al-3 wt.% Sc, and Al-3.6 wt.% Nd master alloys were used. The raw materials were firstly melted in a crucible by heating the furnace to 800 °C and then poured in a cast iron mold at about 720 °C. The compositions of the alloys are given in Table 1. The as-cast alloys were homogenized at 480 °C for 18 h to eliminate interdendritic segregation. After homogenization, the samples were hot-rolled to a reduction of 85% with a temperature of 420 °C, and then annealed at 380 °C for 1 h. The hot-rolled samples were further cold-rolled to a thickness of 1 mm with a reduction of 60%, and then annealed at temperatures ranging from 20 to 550 °C for 1 h.

Microhardness tests were carried out on a HVS-100 Vickers microhardness tester with the loading weight of 9.8 N and the loading time test were performed 15 s. The tensile tests were performed on a CSS-44100 testing machine. And three samples were tested for the microhardness tests experiment and the tensile tests experiment, respectively. The samples for tensile tests were cut along the rolling direction of the plates. Optical microstructures (OM) were observed on a XJP-6A optical microscope. The samples were electro-polished first, then anodized in 2% solution of HBF4 in water. Transmission electron microscopy (TEM) observations were carried out on a TecnaiG^2 20 microscope operated at 200 kV. The thin foils for

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TEM were prepared by a twin-jet technique with an electrolyte solution composed of 30% nitric acid and 70% methanol at a temperature below −30 °C. Electron Back Scattered Diffraction (EBSD) data were obtained on a Sirion 200 field-emission scanning electron microscopy (SEM) equipped with EDAX/TSL XM4-Hikari and TSL OIM 5.31 analysis software. The EBSD specimens were electrolytic polished by 30% solution of nitric acid in methanol at −20 °C.

3. Results and Discussion

3.1 Mechanical Properties

The microhardness curves of the cold-rolled alloys after annealing for 1 h at various temperatures are shown in Fig. 1. It can be seen that the initial and completed temperatures of recrystallization for alloy 1 (Al-Mg-Mn) are about 200 and 300 °C, respectively. However, the initial and completed temperatures of recrystallization for alloy 2 with Nd additions are 225 and 325 °C, respectively; for alloy 3 with Sc additions are 275 and 350 °C, respectively; for alloy 4 with Nd and Sc additions together are 300 and 375 °C, respectively. Therefore, it can be concluded that Nd and Sc elements can increase the recrystallization temperature of Al-Mg-Mn alloy, and the effect of Sc element is more obvious than that of Nd element. Most pronounced improvement of the recrystallization temperature can be obtained by a combined addition of Nd and Sc elements. It may also be noted from Fig. 1 that the microhardnesses of alloys 2, 3, 4 are higher than that of alloy 1 after annealing at the same temperature for 1 h. The microhardness of alloy 3 is higher than that of alloy 2, and alloy 4 has the highest microhardness among the alloys.

Table 1 Chemical compositions of the studied alloys, wt.%

Alloy	Mg	Mn	Nd	Sc	Fe	Si	Al
1	6.52	0.50	…	…	0.15	0.06	Bal.
2	6.50	0.51	0.20	…	0.14	0.05	Bal.
3	6.48	0.49	…	0.20	0.15	0.05	Bal.
4	6.51	0.51	0.10	0.10	0.16	0.06	Bal.

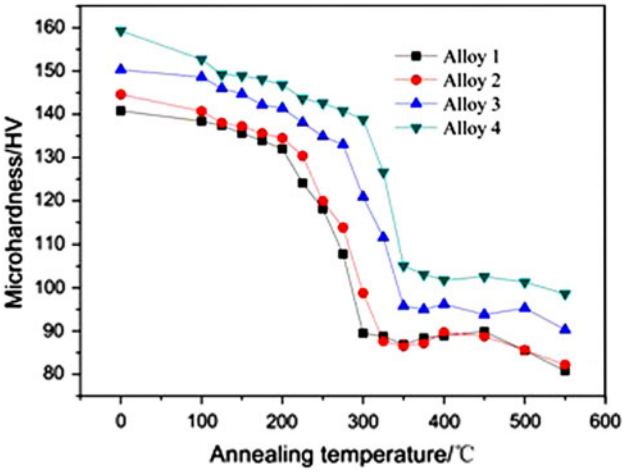

Fig. 1 Variations of microhardness with annealing temperature for the cold-rolled alloys after annealing for 1 h

Tensile properties of the alloys after annealing at 300 °C for 1 h are listed in Table 2. The results show that the strength of the alloy is increased after the addition of Sc or Nd element and the strength increment caused by adding Sc element is bigger than that by adding Nd element. The simultaneous addition of Sc and Nd elements into Al-Mg-Mn alloys (alloy 4) can outstandingly improve the tensile strength and yield strength of the alloy. Compared with alloy 1, the tensile strength for alloy 4 is increased by 65 MPa and yield strength by 55 MPa, respectively. The elongation of alloy 4 is decreased compared with alloy 1; meanwhile, it is clear that adding Nd element can improve the elongation up to 12.5%, which is the most superior among the studied alloys (Table 2).

3.2 Microstructures

Figure 2 presents the microstructures of the four homogenized alloys. It is clear that both the addition of Nd or Sc element and simultaneous addition of Nd and Sc elements can refine the grain size of Al-Mg-Mn alloy by the quantitative analysis using TSL OIM 5.31 analysis software. The most effective refining appears in alloy 4 (Fig. 2d). The average grain size of alloy 1 is about 50 μm, while that of alloy 4 is about 35 μm. These observations indicate that the addition of 0.2 wt.% Nd or 0.2 wt.% Sc into Al-Mg-Mn alloys can bring about a grain refining effect of the homogenization alloys. Better grain refining effect can be obtained by simultaneous addition of 0.1 wt.% Sc and 0.1 wt.% Nd.

Figure 3 shows the EBSD orientation maps of the cold-rolled alloys with and without the addition of Nd and Sc elements after isochronal annealing at the temperature of 300 °C for 1 h. It can be seen that the microstructure of alloy 1 exhibits complete recrystallization (Fig. 3a), and the average grain size is about 10 μm, which is finer than that of the homogenized alloy (Fig. 2a). For alloy 2 with the addition of Nd element, most of the original grains are elongated and there are some fine equiaxed grains appearing along the original in grain boundary (Fig. 3b), showing the characteristics of incomplete recrystallization. The microstructures of alloys 3 and 4 exhibit the structure of cold-work fiber with the original grains elongated and less recrystallized grains distributed along

Table 2 Tensile properties of the annealed alloys

Alloy No.	Alloy composition	Tensile strength, MPa	Yield strength, MPa	Elongation, %
1	Al-6.52Mg-0.50Mn	370	255	11.0
2	Al-6.50Mg-0.51Mn-0.20Nd	380	260	12.5
3	Al-6.48Mg-0.49Mn-0.20Sc	415	293	9.0
4	Al-6.51Mg-0.51Mn-0.10Nd-0.10Sc	435	310	8.0

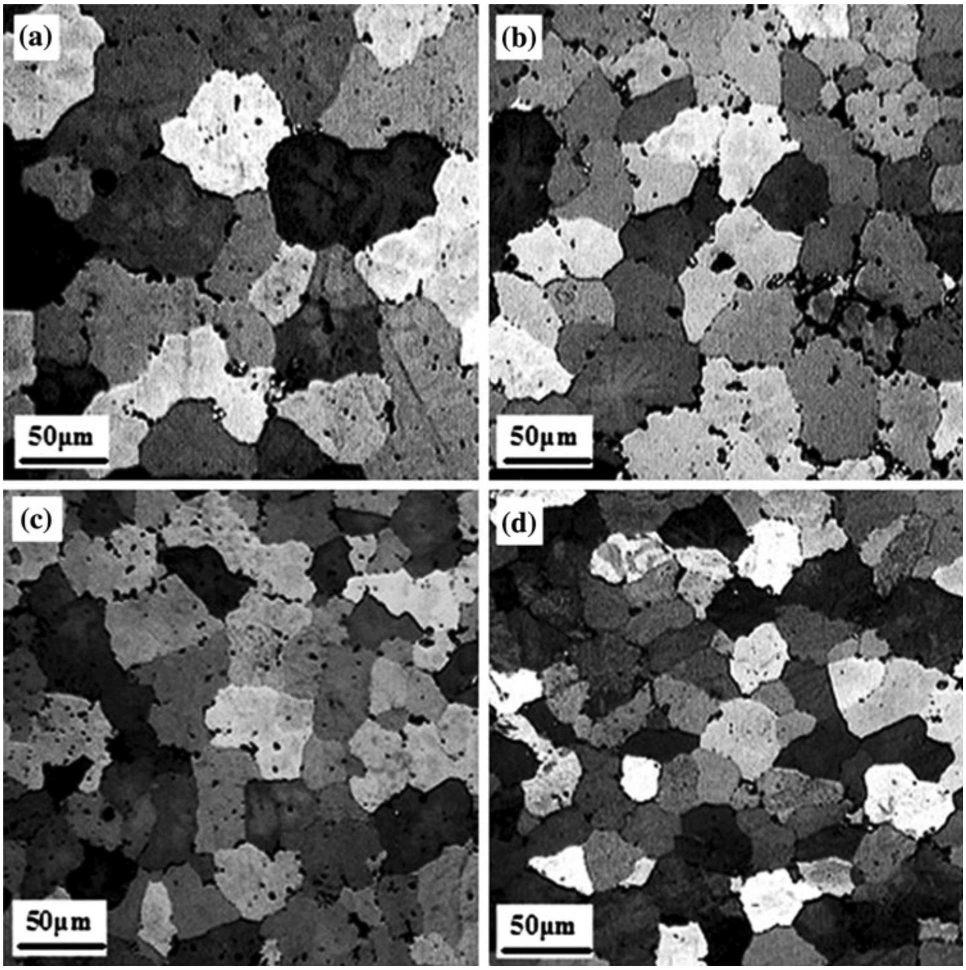

Fig. 2 Optical micrographs of the homogenized alloys with and without addition of Nd and Sc elements: (a) alloy 1, (b) alloy 2, (c) alloy 3, and (d) alloy 4

the original grain boundary (Fig. 3c, d), which indicate that only partial recrystallizations occur.

Al-Mg-Mn alloy is a strain hardening alloy. Cold-rolled deformation can improve the strength of alloy, while annealing would reduce the strength especially when the recrystallization occurs. However, when the grain refining strengthening takes effect in the annealed alloy, the strength would increase with the decrease of the grain size. After annealing at the temperature of 300 °C for 1 h, the complete recrystallization occurs in alloy 1 (Fig. 3a), but incomplete recrystallization in alloy 2 (Fig. 3b) and partial recrystallization in alloy 3 (Fig. 3c) and alloy 4 (Fig. 3d). It can be seen from Fig. 2 that the grains of Al-Mg-Mn alloy are refined after the addition of Nd or Sc element, especially after the addition of Sc and Nd elements together. Under the combined effects of the mechanisms above, the higher microhardness and strength are attained for the Al-Mg-Mn alloy with the addition of small amounts of Nd or Sc element.

Figure 4 shows the TEM morphology of the cold-rolled alloy with the Nd addition (alloy 2) after annealing at the temperature of 300 °C for 1 h. Obviously, the microstructure remains transition state from recovery to recrystallization, and the subgrains can be easily observed. The recrystallization in this alloy is found to be incomplete (Fig. 4), which is in conformity with the result obtained from Fig. 3(b). Therefore, Nd element can improve the recrystallization temperature of Al-Mg-Mn alloy.

When Sc element is added in Al-Mg-Mn alloy, there is some "coffee bean"-like particles with a size of about 50 nm in the grains, as seen from Fig. 5. Previous works (Ref 8, 13-15) have revealed that the "coffee bean-like" contrast is L12-Al_3Sc particles. The Al_3Sc particles are coherent to the matrix, strongly pin dislocations and grain boundaries (Ref 16). Such fine precipitated particles can refine the grain (Fig. 2c, d), and restrain the recrystallization during annealing (Fig. 3c, d), thus improving the recrystallization temperature and the strength of Al-Mg-Mn alloy (Ref 16).

The simultaneous additions of Sc and Nd elements into Al-Mg-Mn alloys not only refine the grains (Fig. 2d), but also increase the recrystallization temperature (Fig. 2) which leads to the formation of a fiber structure after annealing (Fig. 3d). Figure 6 shows the TEM morphology of cold-rolled alloy 4 after annealing at the temperature of 300 °C for 1 h. It can be seen there are not only Al_3Sc particles precipitated in the grains, but also coarse second-phase pinned at the grain boundary (Fig. 6a). EDS analysis of the coarse second-phase in Fig. 6(a) (point A) shows that it is a composite particle mainly containing the elements of Al, Mg, Nd, and the atomic percent of Al, Mg, Nd in the polygon particles is around 66.44, 29.23, 4.33%, respectively. The second-phase is thought to be

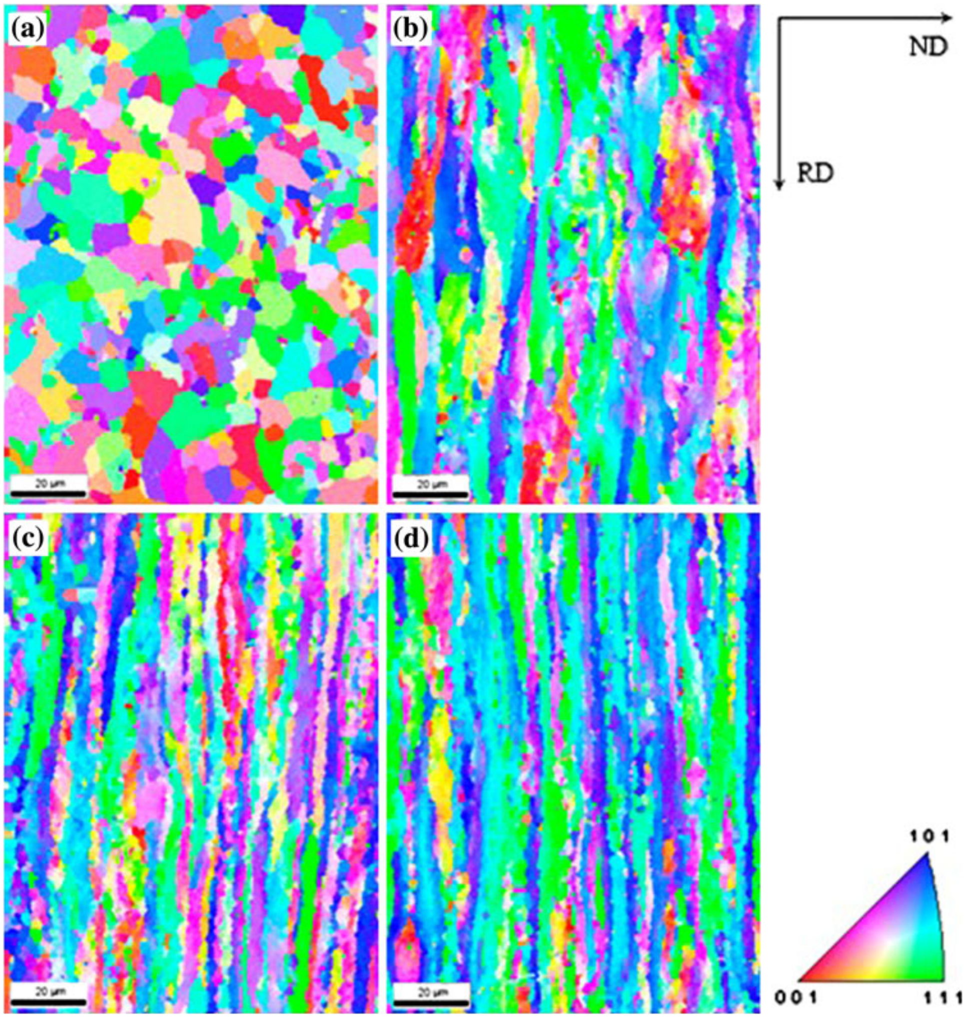

Fig. 3 EBSD orientation maps of the cold-rolled alloys after isochronal annealing at the temperature of 300 °C for 1 h with and without addition of Nd and Sc elements: (a) alloy 1, (b) alloy 2, (c) alloy 3, and (d) alloy 4

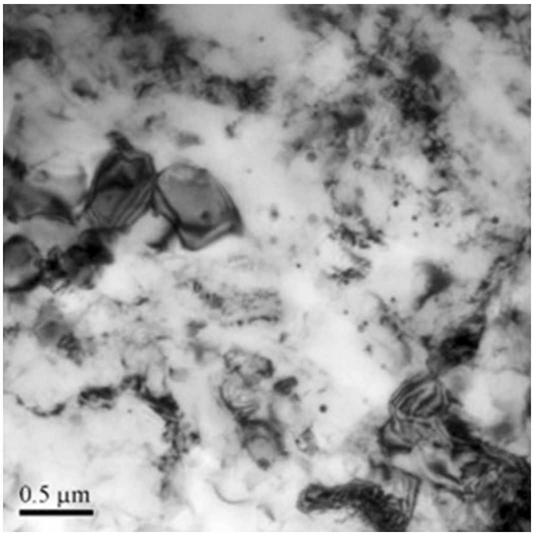

Fig. 4 TEM morphology of cold-rolled alloy 2 after annealing at the temperature of 300 °C for 1 h

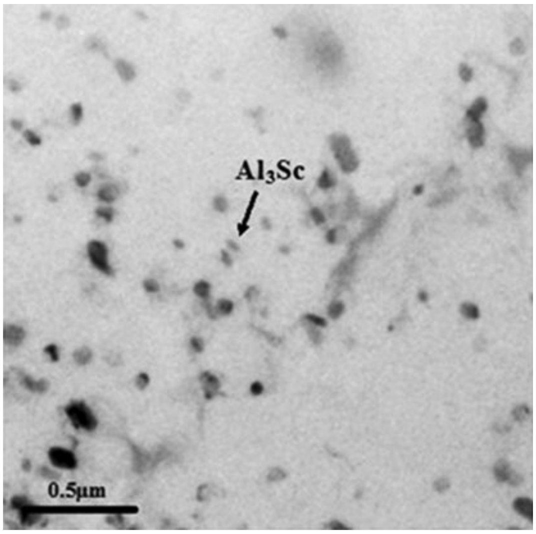

Fig. 5 TEM morphology of cold-rolled alloy 3 after annealing at the temperature of 300 °C for 1 h

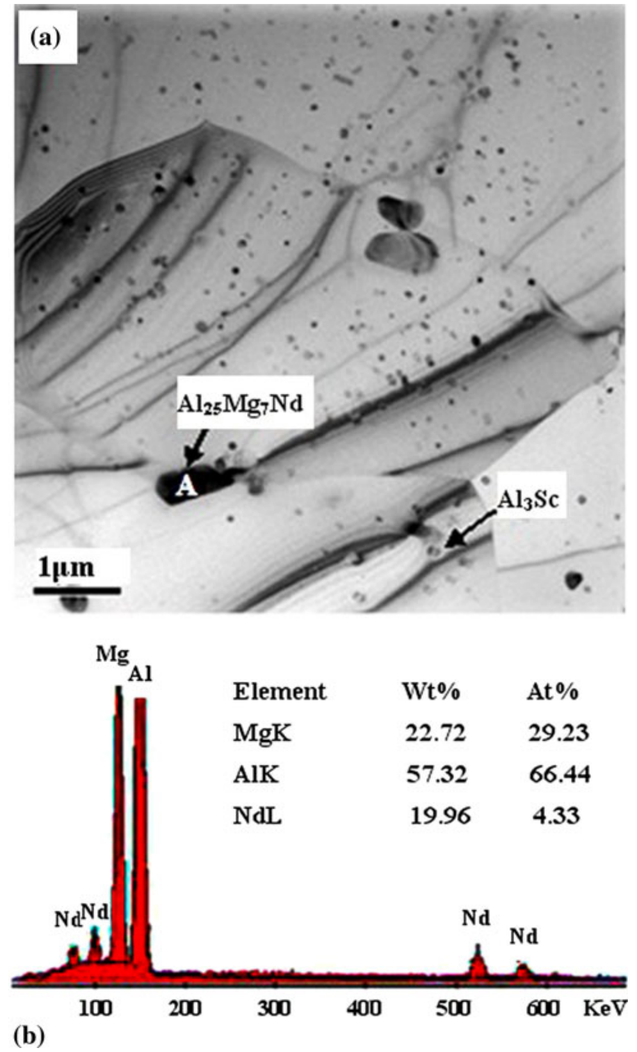

Fig. 6 TEM morphology of cold-rolled alloy 4 after annealing at the temperature of 300 °C for 1 h: (a) morphology of alloy and (b) EDS analysis of point A in (a)

$Al_{16}Mg_7Nd$ phase and the atomic ratio of the second-phase is close to that of the ternary compound $Al_2Mg_{0.88}Nd_{0.12}$, which has been reported by Raghavan (Ref 17). $Al_2Mg_{0.88}Nd_{0.12}$ has the $MgZn_2$-type hexagonal structure with the lattice parameters of $a = 0.5526$ nm and $c = 0.8922$ nm (Ref 17). Therefore, adding Nd element in Al-Mg-Mn alloy, $Al_{16}Mg_7Nd$ phase is formed. The $Al_{16}Mg_7Nd$ phase pinned at the grain boundary can hinder the migration of the grain boundary during annealing process, and thus increase the recrystallization temperature. Meanwhile, it can as well impede the movement of the dislocations, resulting in the improvement of the strength for the alloy.

4. Conclusion

(1) Adding 0.2 wt.% Sc or 0.2 wt.% Nd element to Al-Mg-Mn alloy, the strength of Al-Mg-Mn alloy is increased. Especially, the tensile strength and yield strength of the alloys are greatly improved by a combined addition of 0.1 wt.% Sc and 0.1 wt.% Nd elements. The tensile strength is increased by 65 MPa and yield strength by 55 MPa compared with Al-Mg-Mn alloy. Adding 0.2 wt.% Sc or 0.1 wt.% Sc and 0.1 wt.% Nd elements to Al-Mg-Mn alloy, the elongation is decreased compared with the alloy without addition of Sc or Nd. While, adding Nd element can improve the elongation up to 12.5%. The reason is that Al-Mg-Mn alloy adding 0.2 wt.% Nd exhibits less deformation microstructure and more recrystallization grains comparing with Al-Mg-Mn alloy adding 0.2 wt.% Sc or 0.1 wt.% Sc and 0.1 wt.% Nd elements, and has smaller gain size comparing with the alloy without addition of Sc or Nd.

(2) The grain size of Al-Mg-Mn alloy can be refined after adding 0.2 wt.% Sc or 0.2 wt.% Nd element to the alloy. Particularly, better grain refining effect can be obtained by a combined addition of 0.1 wt.% Sc and 0.1 wt.% Nd elements.

(3) The increase of the recrystallization temperature for Al-Mg-Mn alloy with Nd or/and Sc addition was mainly due to the precipitation of Al_3Sc or/and $Al_{16}Mg_7Nd$ particles. The recrystallization temperature is increased by 100 °C after a combined addition of 0.1 wt.% Sc and 0.1 wt.% Nd elements.

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