Effect of Fe Content on the Microstructure and Properties of Hot-extruded 6061 Aluminum Alloy

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Abstract. The effect of Fe content on the microstructure and properties of Hot-extruded 6061 aluminum alloy was investigated. The results show that the recrystallization process can be effectively inhibited by increasing Fe content appropriately, and consequently affect the grain refinement. After hot extrusion, the iron-rich phase in 6061 aluminum alloy was broken, and fragmented phases are distributed along extrusion direction. After T4 and T6 heat treatment, a large amount of fragmented α-Al(FeMnCr)Si and Mg2Si phases are distributed for the sample with 0.3% content of Fe element. After T6 treatment, the yield strength, tensile strength and elongation of the 0.3%Fe-contenting sample are 298.95MPa, 337.43MPa and 17.88%, respectively. Compared with the hot extruded sample, its tensile strength is significantly increased, about 74.1%, but without noticeable sacrifice of its elongation.

1. Introduction

6061 aluminum alloy is a strengthening Al-Mg-Si alloy by heat-treating. This alloy has been widely used in the fields of construction and aviation due to its high strength, corrosion resistance and good formability[1-3]. Many studies show that about two-thirds of the extruded products are related with aluminum or its alloy, and 90% of these products are made of 6XXX series alloys[4-5].

In the past the research of 6061 aluminum alloy is mainly focused on the as-cast and homogenized alloy. In general, the element of Fe will form brittle phases in the microstructure of castings, which is bad for the mechanical properties. Lin et al. found that lamellar β-AlFeSi phases formed in the as-cast 6061 aluminum alloy with a high Fe content, and these β-phases lead to the decrease of corrosion resistance and mechanical properties[6]. To date, there are a only few studies focus on the effect of Fe content on the deformed microstructures and subsequent heat treatment process. Zhen et al. found that a certain amount of α-Fe dendrites can improve the high temperature tensile strength, delay the propagation of microcracks and neutralize the negative effects of brittle iron-rich phases[7]. Li et al. found that increase of Fe content could effectively inhibit the growth of grains for recycled aluminum, and the grain size can be reduced by up to 25%[8]. A few studies show that when Fe content is lower than 0.3%-0.4%, the mechanical properties of aluminum alloy can be improved, and it is profitable to obtain a finer grain size[9-11]. However, it is not clear whether the formation of iron-containing phase is beneficial effect on the deformed aluminum alloy. In this paper, the influence of Fe element on the microstructure and mechanical properties of the hot extrusion-deformed 6061 aluminum alloy and T4, T6 heat treatment was studied in detail.
2. Experiment
The samples of 6061 aluminum with different Fe content were prepared by smelting. Chemical composition of the sample in this study is showed in table 1.

| Table 1 Chemical composition of 6061 alloy (wt%) |
|-----------------------------------------------|
| Mg   | Si   | Cu   | Cr   | Mn   | Fe  | Al   |
|------|------|------|------|------|-----|------|
| Standard | 0.8-1.2 | 0.4-0.8 | 0.15-0.4 | 0.04-0.35 | 0.15 | ≤0.7 | Bal. |
| Sample1 | 1 | 0.65 | 0.3 | 0.3 | 0.1 | 0.15 | Bal. |
| Sample2 | 1 | 0.65 | 0.3 | 0.3 | 0.1 | 0.3 | Bal. |

The ingots were processed into cylindrical billet of Φ 45 × 100mm by using a lathe. The hot extrusion was carried out on the 600 Tons hydraulic press machine. Each sample was extruded at 450°C under an extrusion speed of 2.2mm/s and using an extrusion ratio of 14. Prior to each pass of extrusion, samples were put into a heat treatment furnace to eliminate the internal stress and obtain a homogenized microstructure. The homogenization treatment was carried out at the temperature of 540°C and with a period of 8 hours. After hot extrusion, T4 and T6 heat treatment were carried out, respectively, in order to further improve the mechanical properties of samples.

The intercepted sample was cut along the longitudinal section. After the mechanical polishing, the samples were anodic coated. The coated liquid is a mixture of fluoroboric acid solution and water, with a volume ratio of 1:32. The microstructure was observed by OLYMPUS-BX 53M metallographic optical microscope and ULTRA PLUS field emission scanning electron microscope. MH-500 microhardness tester was used to measure the hardness. The loading force is 100gf, and keeping time is 10s. Uniaxial tensile tests were performed by using the Machine of Ag-Xplus at room temperature and with tensile speed of 1mm/min. The fracture morphology was observed by ULTRA PLUS field emission scanning electron microscope.

3. Experimental results and analysis

3.1. Optical microstructure
Figure 1 shows the deformation microstructure of 6061 aluminum alloy after hot extrusion. It can be seen from the figure, after the hot extrusion deformation, the grains of the alloy were stretched into slender fibrous structure. Comparing the microstructure of the samples having different Fe content, it can be seen that the elongated grain becomes narrow and a slight recrystallization occurs, as shown in Fig. 1 (a) However, when Fe content increased, the fibrous tissue did not change much. This indicates that a slight increase in Fe content can inhibit the recrystallization process and increase the recrystallization temperature.
Fig. 1 (c)-(f) are the longitudinal section structures of the extruded bars after T4 and T6 heat treatment, respectively. It can be seen that after solution and aging treatment, extruded bars occurred recrystallization in different degrees. It can be found that after T4 or T6 treatment, serious recrystallization phenomenon occurred in sample 1. The fiber tissue becomes wider and the grain size is bigger than the extruded samples. While, the fiber tissue of sample 2 grew up in a lesser degree. And some smaller recrystallized grains can be seen between the fibrous tissues, which may be profitable to improve the mechanical properties.

3.2. SEM testing and EDS analysis

Figure 2 shows the microstructure of the extruded bars after T6 treatment by using Ultra Plus field emission scanning electron microscope. Table 2 shows the chemical compositions of A and B points, which were obtained by EDS analysis.

Table 2 shows that the ratio of (FeMnCr) to Si at point A is 2.08. After removing the content of Si in Mg2Si, the ratio of (FeMnCr) to Si at point B is 2.44. Therefore, it can confirm that the main component of point A is α-Al8(FeMnCr)2Si, and there is a large amount of Cu enrichment. The main composition of point B is α-Al12(FeMnCr)3Si2 and with a small amount of Mg2Si phase.
Combined with the tissue distribution in Figure 1, it can conclude that, after solution and aging treatment, the strengthening phase distribution of sample 2 after crushing is more intensive than that in sample 1. According to the subsequent analysis of mechanical properties, it will demonstrate that the fragmented phases are profitable to improve the mechanical properties of extruded bars.

3.3. Hardness analysis
The relationship between the Vickers hardness of two kinds of extruded bars with different Fe content under different conditions is shown in Figure 3. It can be seen that after solution and aging treatment, the hardness of the extruded bar is significantly improved. After hot extrusion deformation, the hardness of sample 1 is slightly higher than that of sample 2. However, after solid solution and aging treatment, the hardness of sample 2 is higher than that of sample 1. Especially, the hardness of sample 2 reaches to 117.53HV after T6 treatment. After solution and aging treatment, the hardness of the sample with 0.3% Fe content is improved more over than the sample with 0.15% Fe content.

3.4. Mechanical properties analysis
Figure 4 (a)-(c) shows the tensile strength of extruded bars with different Fe contents, and the samples after T4 and T6 heat treatment. Table 3 shows the experimental data of tensile testing including yield strength, tensile strength and fracture elongation. According to Fig. 4 (b), after T4 treatment, the tensile
strength of sample 2 is increased by 59.29 MPa, while that of sample 1 is only increased by 10.66 MPa. After T6 treatment, the tensile strength of the two materials is greatly improved. The tensile strength and yield strength of sample 1 are 312.16 MPa and 337.43 MPa, respectively, and that of are 268.06 MPa and 298.95 MPa, respectively, for sample 2. Compared with the original extruded bars, the tensile strength of sample 2 after T6 treatment is increased by 42.9% and 74.1%, respectively.

| State | Sample | YS/MPa | UTS/MPa | EL/% |
|-------|--------|--------|---------|------|
| Origin | 1      | 121.61 | 218.43  | 21.84|
|        | 2      | 123.39 | 193.81  | 21.83|
| T4     | 1      | 123.14 | 229.09  | 38.75|
|        | 2      | 125.32 | 253.1   | 34.33|
| T6     | 1      | 268.06 | 312.16  | 17.49|
|        | 2      | 298.95 | 337.43  | 17.88|

Figure 4 Effect of T4/T6 treatment on mechanical properties of different Fe content

Above tensile results indicate that the strength of the extruded bars was significantly improved after T6 treatment when the Fe content is 0.3. As it can be seen from Fig. 4 (c), even though increased the content of Fe element, the elongation of the bar can still remain at 17.88% after T6 treatment. According to the above analysis, it is reasonable to conclude that Fe content has a great influence on the mechanical properties, especially the tensile strength of the extruded bars after solution and aging treatment.

3.5. Fracture morphology analysis
Figure 5 (a)-(d) shows the fracture morphology of the extruded bars with different Fe contents after solution and aging treatment in T4 and T6, respectively. It can be seen that after T4 treatment, the small dimples with deeper depth are evenly distributed, and the fracture is typical ductile fracture. However, after T6 treatment, dimples become larger and shallower, and the size of dimples were unevenly distributed, and tearing edges appeared. At the bottom of some dimples, there are some sections separated from the matrix, which can be identified as Fe-containing phase according to EDS. Both
tearing edge and Fe-riched phase leads to the decrease of elongation, which has a harmful effect on the plasticity of materials.

![Fracture morphology of T4/T6 treated 6061 bars with different Fe content](image)

(a) Sample1(T4) (b) Sample2(T4) (c) Sample1(T6) (d) Sample2(T6)

4. Conclusions

(1) Increasing the Fe content appropriately can inhibit the recrystallization process of the material, improve the recrystallization temperature and refine the grain size.

(2) A large number of fragmented Mg$_2$Si and $\alpha$-Al(FeMnCr)Si phases are distributed in the microstructure of 6061 aluminum alloy bars after solution and aging treatment.

(3) When Fe content is 0.3, compared with the original extruded bars, the tensile strength of 6061 aluminum alloy bars treated by T4 and T6 increases by 30.6% and 74.1%, respectively. It is much higher than the improvement degree of the bars with Fe content of 0.15. Moreover, the elongation of the material does not decrease much, and the plasticity remains at an excellent level.

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