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Research microstructure and mechanical properties of AZ31 magnesium alloy by semisolid extruding with electromagnetic stirring process

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Abstract:

To improve AZ31 magnesium (Mg) alloy plasticity, semisolid extruding with electromagnetic stirring process was adopted, and then the mechanical properties and microstructure were studied. The melting temperature was 730°C, and the preheat temperature of the die was set as 300°C, and electromagnetic stirring parameters were 6Hz and 150A with the stirring time 45s, while the rheological extrusion force was 3000KN, the extruding speed was 2mm/s, extruding time was 35s and the extrusion ratio is 10:1. The results show that tensile strength and grain size of AZ31 Mg alloy without rheological extrusion were 174MPa and 124μm, and there were some twins appeared in grains due to the electro-magnetic stirring treatment. With extrusion process, the grain size was refined to 4.91μm, and recrystallization was happened. In addition the tensile strength and the elongation rose up to 206 MPa and 18.35%, respectively, which indicated that the semi-solid processing combined electro-magnetic stirring with extruding technology could improve the tensile and elongation of AZ31 Mg alloy greatly.

Keywords: Magnesium AZ31 alloy; Semisolid extruding; Electromagnetic stirring, mechanical properties

1. Introduction

Mg alloy is one of the lightest structural metal materials, which has distinctive advantages[1, 2], and Mg alloy is also called "environment friendly materials in present and future generations"[3]. In past decades, Mg alloy has been aroused great interests from industries to institutes for its potential applications in aircraft, automotive and electronic industries, et al[4, 5].

However, Mg alloy, as a hexagonal close-packed (HCP) crystal structure, has only a set of basal plane slip system that can be activated at room temperature, which leads to its poor plasticity[6]. Improving room temperature plasticity of Mg alloy can greatly extend its applications to structural parts. For example, the material used in automotive shell requires not only excellent cold stamping properties, such as excellent ductility and deep draw ability, but also high specific strength and sufficient plasticity[7]. Therefore, improving the strength and plasticity of Mg alloy becomes a very urgent mission for its future potential application.

Due to the inherent characteristics of Mg alloy, it is very hard to get a high performance Mg alloy product by traditional forging and casting method with high quality and low cost[8, 9]. Semi-solid processing technology provides a possible solution to overcome the weakness of traditional casting and forging method, which can not only effectively avoid metallurgical defects appeared in traditional casting method, but also require relative low power of equipment to produce a complexity structure part compared with traditional forging method.

In general, semi-solid forming can be divided into rheological forming and thixoforming according to its forming method[2]. The thixoforming needs to strictly control the heating temperature, pressure and holding time to prevent microstructure growth[10, 11], which means that the thixoforming needs more strictly process parameters and more energy consuming. On the contrary, the rheological has advantages of good fluidity, low power requirement, low cost and easily operating[2]. Therefore, in this paper, the rheological method combined with electronical stirring method and extruding method was adopted to produce high performance with ultrafine grains AZ31 Mg alloy ingot.

2. Experimental material and process

The experimental material is commercial AZ31 Mg alloy, and its chemical composition is listed in Table 1. The solidification curve of AZ31 Mg alloy was measured to get the liquidus, and the liquidus temperature of AZ31 is 628°C, as shown in Fig.1.

Firstly, the crucible was cleaned before the experiment, the anhydrous ethanol mixed with zinc oxide was stirred and coated on the inner surface of crucible pot. After the coating layer was ignited, the crucible pot was preheated to 300°C with 10-20 minutes.

Table. 1 Chemical composition of AZ31 Mg alloy (wt. %)

Model	Mg	Al	Si	Ca	Zn	Mn	Fe	Cu	Ni
AZ31	rest	2.5-3.5	0. 08	0. 04	0.6-1. 4	0.2-1. 0	0. 003	0. 01	0. 001

Then AZ31 Mg alloy was placed in a KWG-15-19 type furnace. According to the solidification curve of AZ31 Mg alloy, the heating temperature was preset 730°C. When the well type furnace was preheated to 300°C, the Mg alloy was placed in a furnace and heated up to 730°C. During the AZ31 Mg alloy melting process, sulfur hexafluoride (SF_6) gas was adopted to keep the AZ31 Mg alloy from oxygen touching. In order to effectively and safely use sulfur hexafluoride (SF_6) gas , nitrogen (N_2) gas was mixed with SF_6 gas in the furnace to reduce SF_6 gas consumption, and N_2 gas can also carry SF_6 more effectively. The ratio of N_2 to SF_6 was 100:1. At beginning of this experiment, the protective gas was introduced into the furnace until the AZ31 Mg ingot was completely melted. Simultaneously, the extruding mold was placed in a box-type electric resistance furnace and was preheated to 300°C.

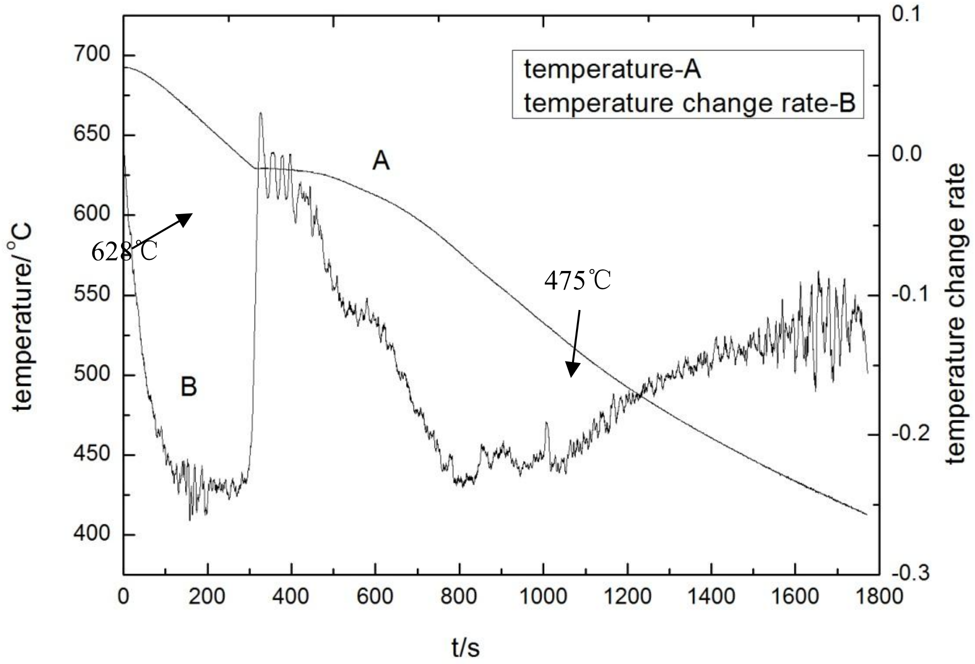


Fig. 1 Solidification curve of AZ31 Mg alloy

During solidification process, a TSDG3-J electromagnetic stirrer was employed. When the AZ31 Mg alloy in the crucible furnace was completely melted, and then electromagnetic stirring was exerted on the liquid with parameters of 6Hz and 150A during the solidification process. When the Mg alloy was in semi-solid state, it was extruded by YH61-500G hydraulic pressure machine and the rheological extrusion pressure was 3000KN for 35s, extrusion speed was 2mm/s and the extrusion ratio was 10:1. Meanwhile, the protective gas was continuously introduced to prevent oxide generation during the electromagnetic stirring process.

The schematic figure of the AZ31 Mg alloy extruding mold was shown in figure 2a), and the real extruding sample was exhibited in figure 2b). The DK77 series wire-cutting machine was used to produce the standard tensile test specimens and metallographic observation specimens, and the specimen was selected in the bottom side of extruding sample. The microstructure was observed by OLYMPUS BX60 metallographic microscope. Before the optical observation, the samples were polished firstly, and then the samples were corroded with a solution of 0.5g of picric acid, 1ml of glacial acetic acid, 1ml of distilled water and 7ml of alcohol. The corrosion time was 10s. Mechanical properties were measured on WGW-100H universal tensile testing machine.

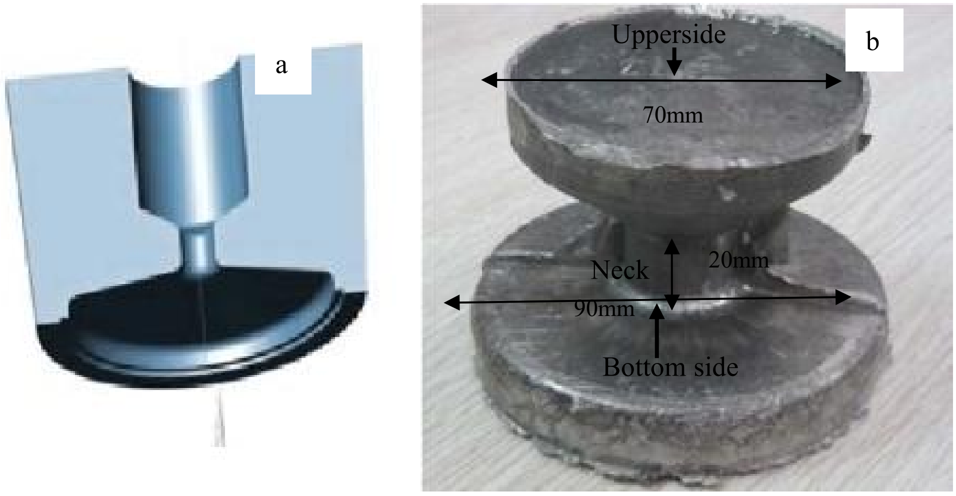


Fig. 2 3D figure of extruding mold and real semisolid extrusion casting sample, a) extruding mold, b) extruding sample

3. Experimental results and analysis

3.1 Preparation of semi-solid billets

Electromagnetic stirring technology is a relatively effective method to refine grain and enhance the final properties. To get the optimized electromagnetic stirring parameters, numerical simulation method was adopted to simulate the rotating magnetic field in three dimensions to obtain electromagnetic force distribution, and the flowchart of numerical simulation could be seen in Fig.3. In this experiment, the electromagnetic stirrer internal structure was mainly consisted of two parts, one part was the stator composed of coils and internal wiring was star type connection, which schematic figure was illustrate in Fig.4, and the other part was the rotor that was the liquid metal.

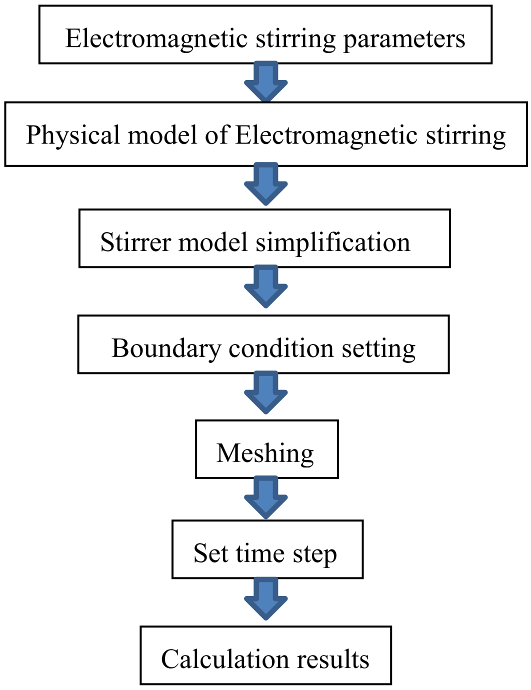
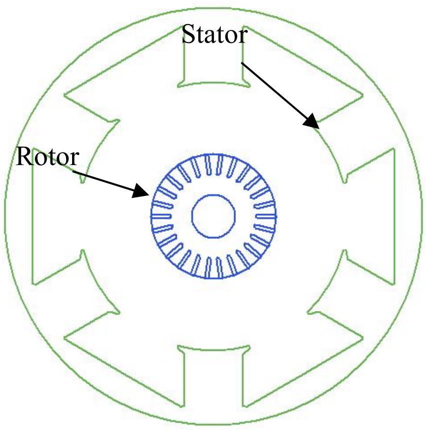


Fig. 3 Simulation flowchart

To simplify the simulation process, the physical properties of AZ31 Mg alloy was assumed as constant without changing during liquid/solid transformation, and the multi-coils were simplified into conductive models to reduce computing time and enhance the calculating efficiency. According to the experimental stirring parameters, the maximum and minimum magnetic field intensity under 6HZ 150A were 0.20124T and 0.199T, respectively, as shown in Fig. 5.



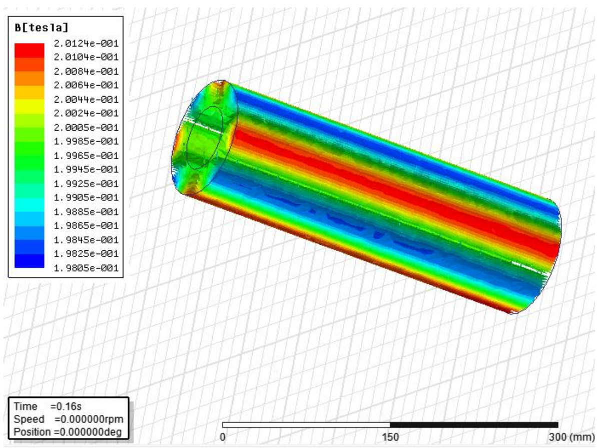


Fig. 4 Electromagnetic stirring structure **Fig. 5 Electromagnetic induction intensity**

Under 6HZ and 150A condition, the average electromagnetic force was calculated, and the maximum electromagnetic force was 2.1354N while the average electromagnetic force was 1.9356N, as shown in Fig. 6.

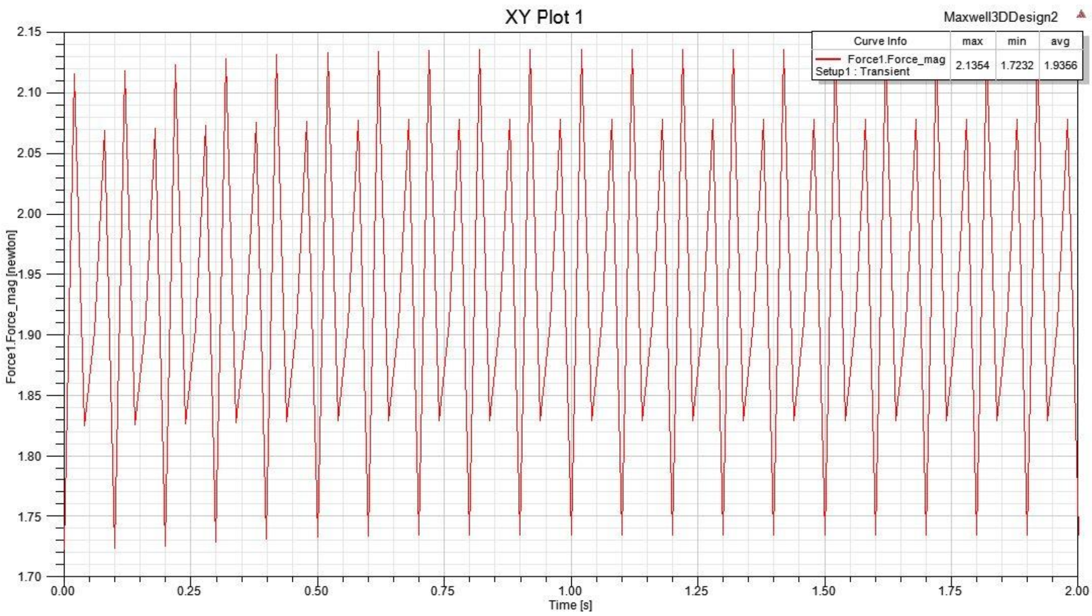


Fig. 6 Electromagnetic force distribution

Due to the electromagnetic force on Mg alloy liquid, the forced flow caused by Lorentz force can break the dendritic arm into smaller crystals, and these smaller crystals form the new grain, which refines the grain size. Furthermore, the Lorentz force can also take the solidified dendrite rotate that reduces the constitutional undercooling ahead of dendrite tip and makes its shape become spherical shape. In addition, the Lorentz force can give rise to plastic deformation of the solidified dendrites. As the above mentioned reasons, the number of nuclei increases and the grain size gradually decreases, and the morphology of grain gradually tends to spherical shape during the electromagnetic stirring process.

Figure 7 shows the microstructure of AZ31 Mg alloy after electromagnetic stirring, in which red arrow pointed to is α-Mg matrix and blue arrow pointed to is β-$Al_{12}Mg_{17}$ phase. From Fig.7 a) it can be seen that $Al_{12}Mg_{17}$ phase are distributed evenly in Mg matrix and the microstructure tends to be refined and round shape without dendritic morphology. In Fig.7 b) there also are some twins as green arrow pointed to, which prove the plastic deformation happened in grains during electromagnetic stirring solidification process. After electromagnetic stirring, the tensile strength and average grain size are 174MPa and 124μm, respectively. Due to the mold preheating temperature 300℃, it takes long time to cool down that leads to the grains have enough time to grow up, which is the main reason caused the large grain size and relative low tensile strength.

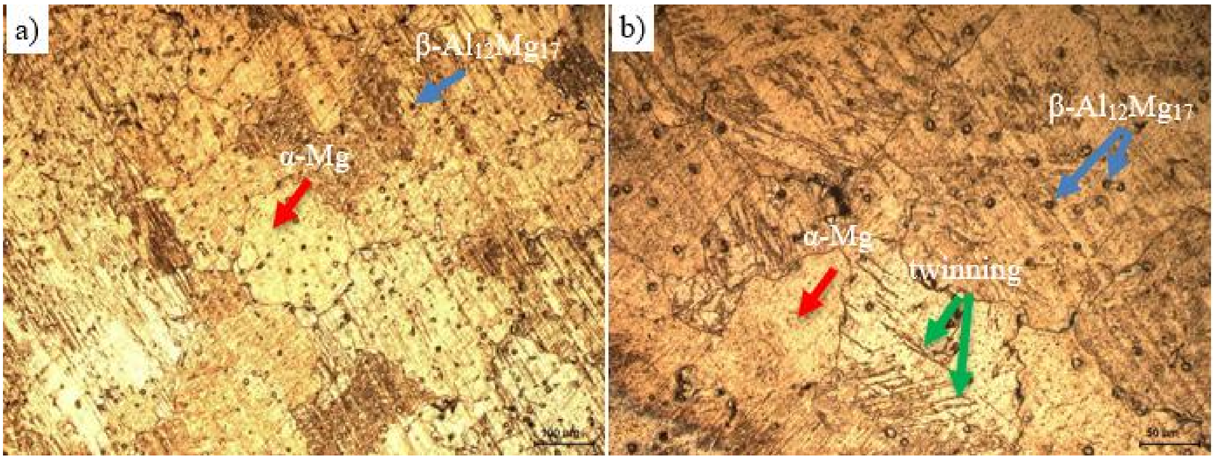


Fig. 7 Microstructure of semi-solid extruding specimen, a) scale size is 100μm, b) scale size is 50μm

3.2 The effect of extrusion on the microstructure

In order to illustrate the effect of extrusion on microstructure, the crystal lattice size of casting state and extruding state are compared, in which the crystal lattice size was derived from XRD measured results. The calculated result was shown in Table 2.

Table 2 lattice size of AZ31 Mg alloy by casting and extruding[11]

Status	a/nm	c/nm	c/a
Cast state	0.3192	0.5181	1.6231
Extruding state	0.320431	0.51995	1.6226

Tu Yifan[12] et al used XRD analysis on the as-cast state of AZ31 Mg alloy compared with the extruded state, and found axis ratio *c/a* of α-Mg decreased. Under extruding conditions, the values of *a* and *c* were all increased, which indicated there was distortion in crystal structure, and the distortion could lead to the layer fault, dislocations, and twins appearing in grains and leads to Mg alloy tensile strength increasing.

After rheological extrusion of AZ31 Mg alloy, microstructure was shown in Fig.8, which indicated that the grains were very fine and the average grain size was 4.91μm, which was much smaller than 124μm in the original semisolid state.

As the semi-solid slurry first entered the mold, especially through the neck part of mold (as shown in Fig.2), the semi-solid slurry enduring the great deformation and its flow rate rised sharply, which broke the original solidified part into much smaller grains. When the slurry reached the bottom side of the mold, the slurry would nucleate rapidly and form more fine grains because of the relative lower mold temperature(the mold temperature 300℃ is much lower than the melting point of AZ31 Mg alloy). Whe the mold was pouring fully, the continuously pressure exerted on the slurry could also break the grains into more refined grains. In addition, due to the mold extrusion ratio was 10:1, the large deformation with preheated 300℃of mold temperature could lead to recrystallization occurred. In generally, in Mg alloy, dynamic crystallization mainly depends on stacking fault energy and the stacking fault energy of Mg is only 78 mJm^{-2}[12]. Therefore, it is much easier to generate dynamic crystallization and refine grains.

In figure 8 a), it is found that the averaged grain size drops to 4.79μm, and some grain size can reach about 20μm while the other small grain size can reaches 1-2μm, which means that the grains have experienced incomplete recrystallization, the very fined grains are recrystallized grain, and the large grains are extruded grains. In Fig.8 b), it is shown that with the electromagnetic stirring treatment and rheological extruding process, the orientation of grains appear strong direction paralleled to Z direction (extruding force direction), which reflects the fact that the crystallization occurs during rheological extruding process and the new grains nucleate and growth prefer to be parallel to extruding force direction, while the original solid part tends to rotate to this direction under the extrusion condition.

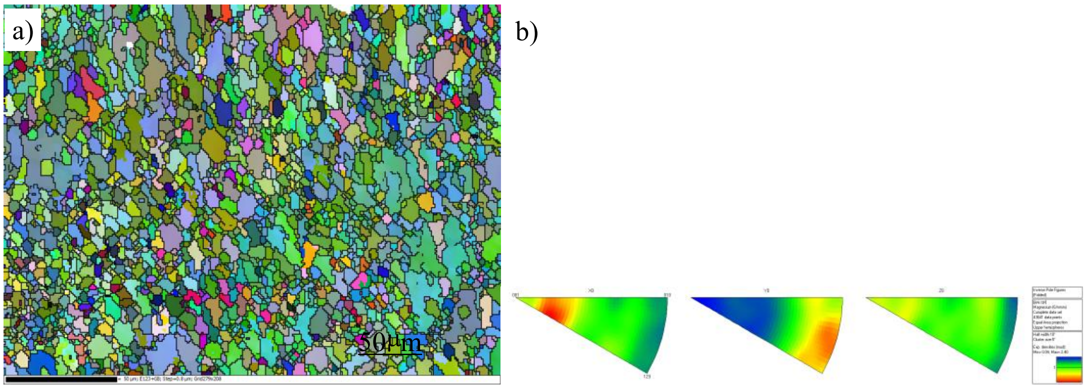


Fig. 8 Microstructure of bottom specimen, a) microstructure, b) orientation distribution in *x*,*y* and *z* direction

The mechanical properties after rheological extruding process was shown in Figure 9 that the tensile strength and elongation reached 206MPa and 18.35%, respectively, and the tensile strength increased 18% higher than semisolid state, which indicated that the finer grain could not only increase tensile strength, but also could improve its elongation of AZ31 Mg alloy apparently. According to Hall-Petch law, the finer grain size is, the higher strength gets, which is the main reason of higher tensile strength. When the grain size is much finer, in this experiment only 4.79μm, which leads to more grain boundary appearing and make grain boundary slipping become one of the reason of good plasticity performance besides the inner grain dislocations and twins resulted in plasticity performance.

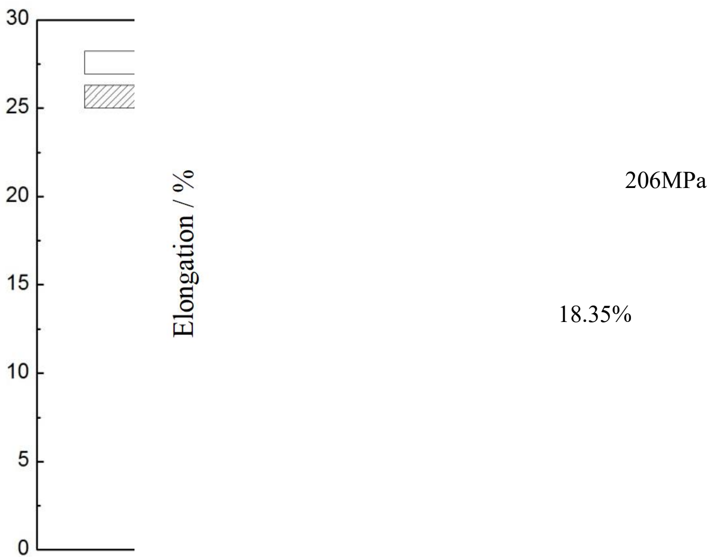


Fig. 9 Tensile strength and elongation after rheological extruding AZ31 Mg alloy

4. Conclusions

In this paper, semisolid processing combined with electro-magnetic stirring treatment and extruding process of AZ31 Mg alloy was adopted, and the microstructure and mechanical properties of AZ31 alloy are studied and the following conclusions were drawn:

(1) Without extruding process, the tensile strength and grain size of AZ31 Mg alloy were 174MPa and 124μm, and there were some twins in grains due to the electro-magnetic stirring treatment.

(2) Under the extruding ratio 10:1, the grain size of AZ31 Mg alloy was dropped greatly from 124μm to 4.79μm, and the tensile strength and elongation of AZ31 Mg alloy were rose up to 206 MPa and 18.6%, respectively.

(3) The incomplete recrystallization were happened during semisolid processing combined with electro-magnetic stirring treatment and extruding process, which led to grain refining.

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