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# Preparation of AZ31 magnesium alloy strips using vertical twin-roll caster

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**Abstract:** A newly developed technology for manufacturing magnesium alloy strip, vertical twin-roll strip casting, has been described. This manufacturing process is easy to be facilitated in an economical way to manufacture wrought magnesium alloy strips. As an example, AZ31 magnesium alloy was used to investigate the appropriate manufacturing conditions for vertical twin-roll strip casting by varying the temperatures of the molten materials and rolling speeds. The effects of manufacturing conditions on forming quality were clarified in terms of roll speeds and casting temperature. In addition, microscopic observation and X-ray diffraction of the as-cast strips were performed. It has been determined that AZ31 alloy strip of 1−3 mm in thickness can be produced at a speed of 30 m/min by a vertical twin-roll caster. The microstructure of as-cast strip only contains $\alpha$-phase (Mg) and no other phase, and the twin-roll casting process can effectively refine the grain size. The fine equiaxed grain of as-cast strips is beneficial to the plastic deformation of the strips, and it is also suitable for direct cold-rolling with a maximum cold-rolling reduction of 40%.

**Key words:** AZ31 magnesium alloy; vertical twin-roll casting; cold rolling; microstructure; tensile properties

## 1 Introduction

Magnesium alloy is the lightest metal among all the structural metals, and is also the third most-abundant structural metal following steel and aluminum. The demand of magnesium alloys has been rapidly increased in recent years in order to meet the environment and sustainable development. With the growing applications for weight-saving and energy-saving, magnesium and its alloys are regarded as structural and functional materials due to their high specific strength, high damping and good electromagnetic shield abilities[1−3]. Most magnesium alloy components have been produced by various die casting processes for its good casting behavior[4−5]. Despite the fact that wrought flat products are more convenient to use, less than one percent of magnesium alloys are provided as sheets because wrought magnesium sheets are now still quite expensive and difficult to produce[6]. Therefore, the development of new forming processes for magnesium sheets is expected in order to lower the production cost and extend the application fields.

Strip casting is the most innovative development in metal shaping process in recent years. During a strip casting process, the molten metal is poured into a space formed by two rotating rolls and side dams, then starts to solidify at the point of first metal−roll contact and ends before the kissing point, where rolling deformation occurs when the thickness of solidified shells exceeds the gap between the rolls. Strip casting is a process that integrates the casting and hot rolling in one step and it can produce as-cast strips with a thickness of 1−10 mm. This technique has potentials in considerable cost saving, easy-operation and maintenance etc[7−10].

As for magnesium alloy strip manufacturing, there are a lot of research works and some economical manufacturing techniques have been developed to produce high-quality AZ31 magnesium alloy strips [11−15]. In this work, we use vertical twin-roll casting process to manufacture AZ31 magnesium alloys strip and the influence of processing parameters, e.g. roll speed, casting temperature, and performed gap, on the microstructures and mechanical properties of as-cast magnesium alloy AZ31 is discussed. Based on this, the as-cast magnesium alloy strips have been cold-rolled

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directly for producing high quality strips.

## 2 Experimental

A vertical-type twin roll caster was used to manufacture thin strips of AZ31 magnesium alloy. A pair of Ni-Cr alloy rolls was used for the vertical-type twin-roll caster. Fig.1 illustrates the vertical twin-roll strip casting procedure. The specifications of the caster are listed in Table 1.

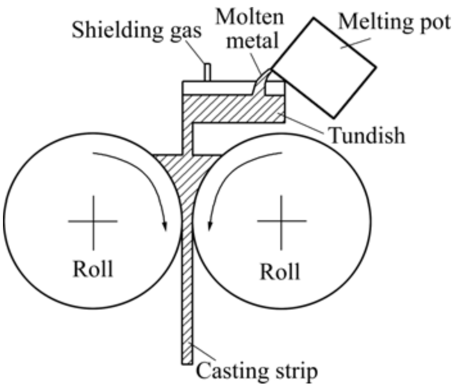


**Fig.1** Schematic diagram showing manufacturing process of AZ31 alloy with vertical twin-roll caster

**Table 1** Specifications of vertical pilot twin-roll caster

| Item | Specification | Remark |
|---|---|---|
| Roll diameter/mm | 500 | Ni-Cr alloy |
| Roll width/mm | 254 | – |
| Power of drive motor/kW | 5 (Alternative current) | Variable frequency |
| Casting speed/(m·min$^{-1}$) | 5−30 | |
| Strip thickness/mm | 1−3 | |
| Separating force/N | 0−10 000 | |
| Tundish | | Refractory |
| Side dam | | Quartz |
| Protection gas | $CO_2$, Ar, no shield | |

The material employed was commercial AZ31 magnesium alloy billets with chemical composition of Mg-3%Al-1%Zn-0.4%Mn (in mass fraction, %). Magnesium ingots were firstly heated to 720 ℃ in a crucible in an electric furnace. Refining was then conducted when the temperature was lowered to 700 ℃. After that, it was cast at a predefined temperature. During melting process, impurities like magnesium oxide and other suspended nonmetallic matter were removed with flux that preferentially wet the impurities and carried them to the bottom of the crucible. After refining, the molten magnesium alloy was finally carried to the strip caster and poured into the tundish to prepare magnesium alloy strips.

The casting conditions are as follows. Casting speeds are 10, 15, 20, 25 and 30 m/min and pouring temperatures are 640, 650 and 660 ℃. After casting, the cast strips were homogenized at 350, 400 and 450 ℃ for 1 h and air cooled to room temperature to improve the mechanical properties of strip. The mechanical properties were measured using a MicroTest Instron 5848 (Norwood, MA) with a tensile speed of 2 mm/min. The specimens for OM, XRD and TEM were prepared by the standard technique of grinding and polishing.

## 3 Results and discussion

### 3.1 Manufacturing conditions and shape defects

Twin-roll strip casting is a complex process, which contains high-speed solidification from high temperature and simultaneous rolling. Any minor change in one of the processing parameters will cause instability in roll-casting, leading to strip defects or process interruption. For example, if roll-casting speed is too high, magnesium alloy liquid leakage will occur due to the decrease of the thickness of solidified shells. Otherwise, ultimate freezing point will increase with the increase of the thickness of solidified shells, which can easily lead to cracks in solidified high-temperature strips because of the plastic deformation or cause a rolling block in severe case. In the experiment, when the casting speed is higher than 30 m/min, the melting magnesium alloys is not completely solidified, So, a continuous casting is thus unsuccessful. Appropriate rate gets lower at a roll-casting temperature of more than 660 ℃, mainly because at higher roll-casting temperature, the longer time is needed for solidification exchange. Therefore, at this time, under a larger casting speed, it is easy to get a failure of the roll-casting due to incomplete solidification. It is found in experiment that the forming casting speed range of magnesium alloy is wide enough to obtain a good strip with a superheat of 10−20 ℃.

Fig.2 shows the surface morphology of as-cast AZ31 magnesium alloy strip manufactured by vertical twin-roll caster. The product was manufactured at a roll speed of 20 m/min and a casting temperature of 650 ℃. It is seen that the surface of the as-cast strip is not oxidized too much in the air, even without any protective atmosphere during the strip casting. Generally, the surface of the as-cast sheet is smooth and has no cracks.

Fig.3 presents typical cracks found in the as-cast AZ31 strip. Generally, the cracks occur at the mid and near the edge of the as-cast sheet. During the twin-roll casting process, the outer solidified shell was cooled more quickly than the inner layer, rendering more shrinkage in the outer surface than the inner layer of the shell. The difference in shrinkage will generate a tensile

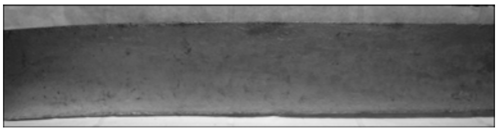

**Fig.2** Surface morphology of as-cast AZ31 magnesium alloy strip

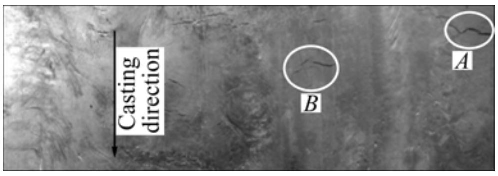


**Fig.3** Cracks in as-cast AZ31 magnesium alloy strip

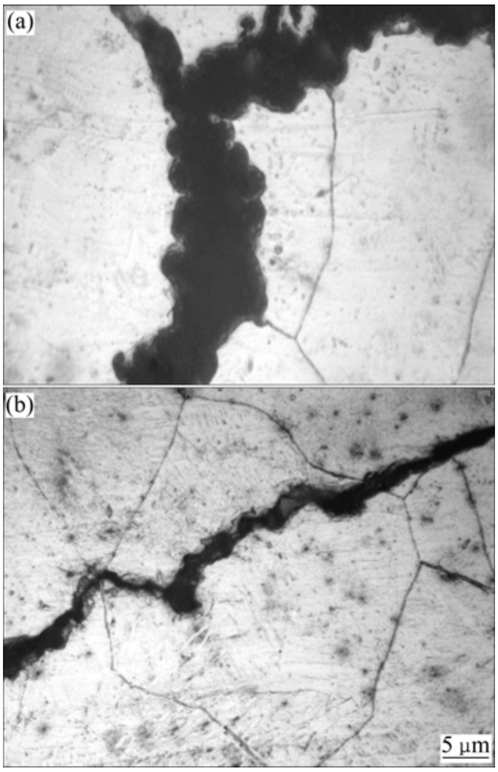


**Fig.4** Morphologies of cracks occurring in strip corresponding to circles *A* (a) and *B* (b) in Fig.3, respectively

stress at the outer surface of solidified shell and a compressive stress at the inner layer. Fig.4 shows the microstructures of two types of strip cracks with one along the grain boundary (Fig.4(a)) and the other propagating through the grain (Fig.4(b)).

### 3.2 Microstructure of as-cast strips

Fig.5 shows the microstructures of as-cast AZ31 magnesium alloy sheets obtained by vertical twin-roll casting at a roll speed of 25 m/min. The as-cast products exhibit an equiaxed grain structure, with average grain size ranging from 15 to 20 μm at both the roll surface side (Fig.5(a)) and the mid of the cross-section (Fig.5(b)).

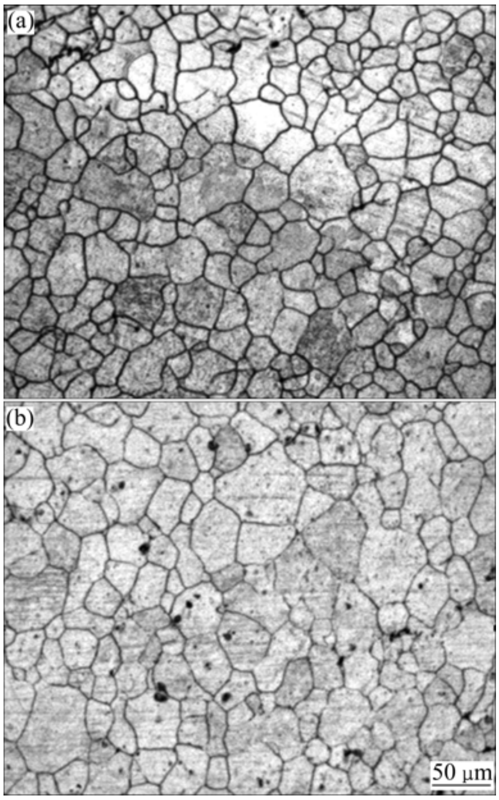


**Fig.5** Microstructures of as-cast AZ31 magnesium alloy strip ($v$=25 m/min): (a) Roll surface side; (b) Mid of cross-section

Fig.6 shows the microstructures of the as-cast AZ31 strip obtained by vertical twin-roll casting at a roll speed of 15 m/min and a casting temperature of 635 ℃. The head (Fig.6(a)) and middle (Fig.6(b)) parts of the as-cast sheet have equiaxed grain structure, while the tail section (Fig.6(c)) exhibits both dendritic and equiaxed structure. Dendrite fragmentation is also found in the tail section except for the dominant dendritic and equiaxed structure. Generally, the head and middle parts have similar grain sizes, with an average of approximately 22 μm. However, fine grains less than 10 μm in diameter are also present in the as-cast sheet. The instability of the casting might result in slight structural irregularity. So, a well-controlled casting velocity and temperature may improve the homogeneity of the strip structure.

The XRD patterns of the as-cast magnesium alloy strips are shown in Fig.7. As-cast AZ31 magnesium alloy strips with different casting speeds have the same XRD diffraction pattern with all the peaks in approximately the same locations. However, the intensities of the diffraction peaks increase with increasing the casting speed. We know that when the casting speed is increased, cooling will be promoted, resulting in much finer grains. The magnesium alloy strips with finer grains give X-ray diffraction patterns increased intensities. All the X-ray diffraction peaks correspond to $\alpha$-phase (Mg) and no

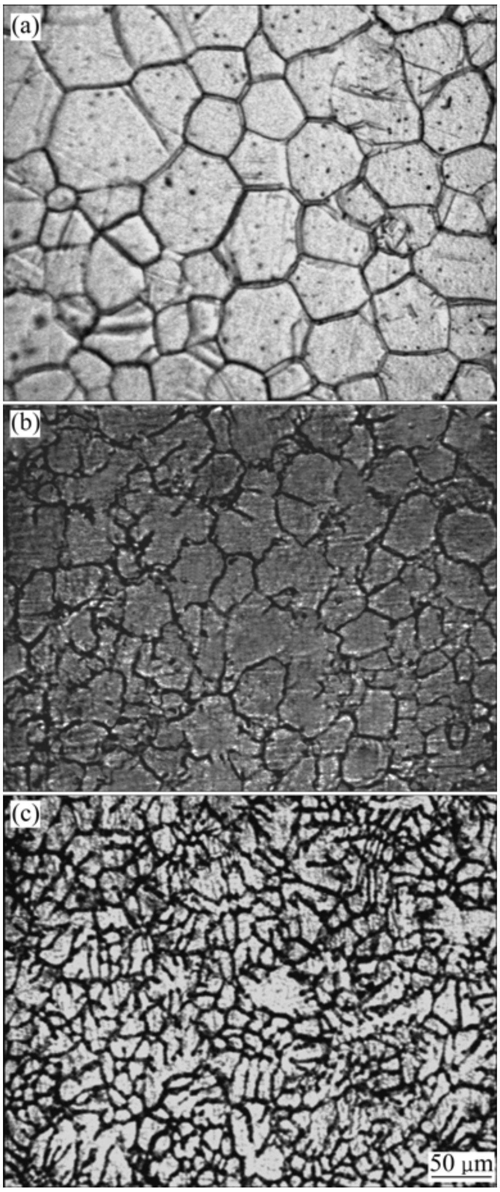


**Fig.6** Microstructures of as-cast AZ31 magnesium alloy strip ($v$=15 m/min): (a) Head region; (b) Middle part; (c) Tail section

$\gamma$-phase ($Mg_{17}Al_{12}$) has been detected in the as-cast AZ31 magnesium alloy strips. However, aluminum may exist in the solid solution state. The reason for not containing $\gamma$-phase in XRD pattern can be interpreted as follows. The melted magnesium alloy is cooled quickly during the vertical twin roll casting. Accordingly, not sufficient time is allowed for aluminum to diffuse and get evenly distributed during the $L\rightarrow\alpha$ transformation process, resulting in the enrichment of aluminum in liquid solution with content much higher than its solubility. The eutectic transformation does not occur due to the very limited time allowed for solidification, which results in a supersaturated solid solution rich in $\alpha$-Mg. The absence of the brittle $\gamma$-phase in the as-cast strip indicates that the plasticity of the magnesium alloy is improved by casting.

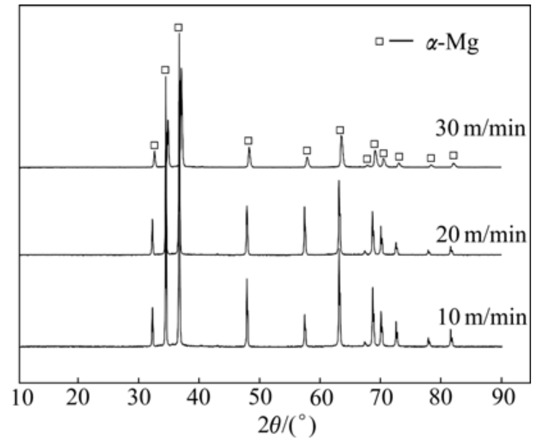


**Fig.7** XRD patterns of as-cast AZ31 magnesium alloy strips with different casting speeds

TEM image (Fig.8(a)) shows that many dislocations exist in the as-cast AZ31 magnesium alloy during vertical twin-roll casting. Generally, the plastic deformation takes place immediately after the cast-rolled AZ31 magnesium alloy is solidified. Consequently, it occurs at a temperature close to the solidifying point, at

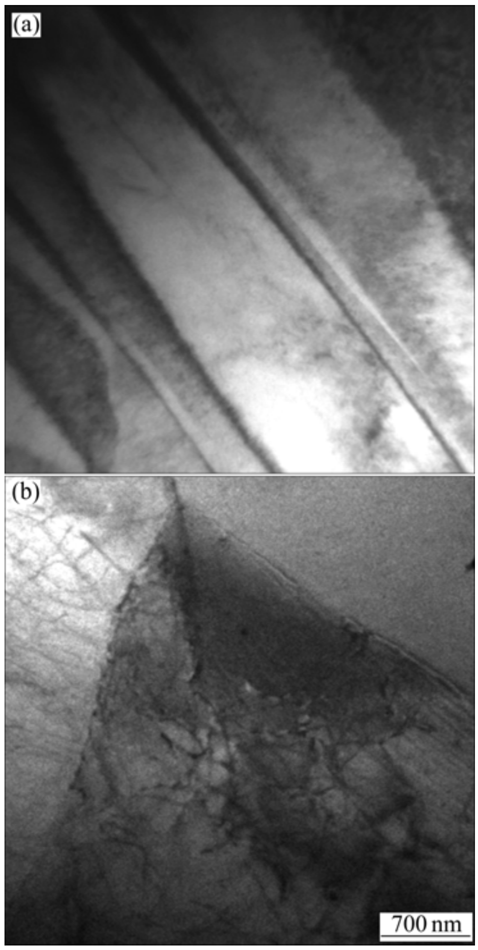


**Fig.8** TEM images of cast AZ31 magnesium alloy strip: (a) Twin; (b) Dislocation pile-up

which the slip systems of the base planes, prismatic planes and the conical planes are all active. As the deformation continues, dislocations multiply and move. Dislocation networks will form when dislocations of different slip systems interact and tangle, as shown in Fig.8(b).

### 3.3 Mechanical properties of as-cast AZ31magnesium alloy strips

Mechanical properties of as-cast strips under different processing conditions are measured and compared, as listed in Table 2. The tensile tests were carried out at room temperature and a strain rate of 2 mm/min.

Rapid solidification process can refine the grain size and the mechanical properties of strips are improved. Fig.9 shows the microstructures of the as-cast AZ31 magnesium alloy strips at different casting speeds. It can be seen that the microstructures of the as-cast strips vary with casting speed. This difference in microstructure results in different mechanical properties, as shown in Table 2. Strip A has a relatively high ultimate tensile strength (UTS) (149 MPa) in as-cast state due to the uniform rosette-like and crush dendrite microstructure in all cross-sections of the strip. Strip B contains fully developed dendrite, which leads to higher UTS of 182 MPa. While strip C has the highest UTS (234 MPa) in the as-cast state, which is attributed to the uniform equiaxed grain microstructure in all cross-sections of the strip. Actually, strip C is cast at the maximum speed of the caster, resulting in a much thinner strip and much finer grains. The mechanical properties are improved by increasing the casting speed. Fig.9 shows the microstructure observed in the central part of the strips, which is always solidified at last. This demonstrates that the microstructure shown in Fig.9(a) will be obtained at

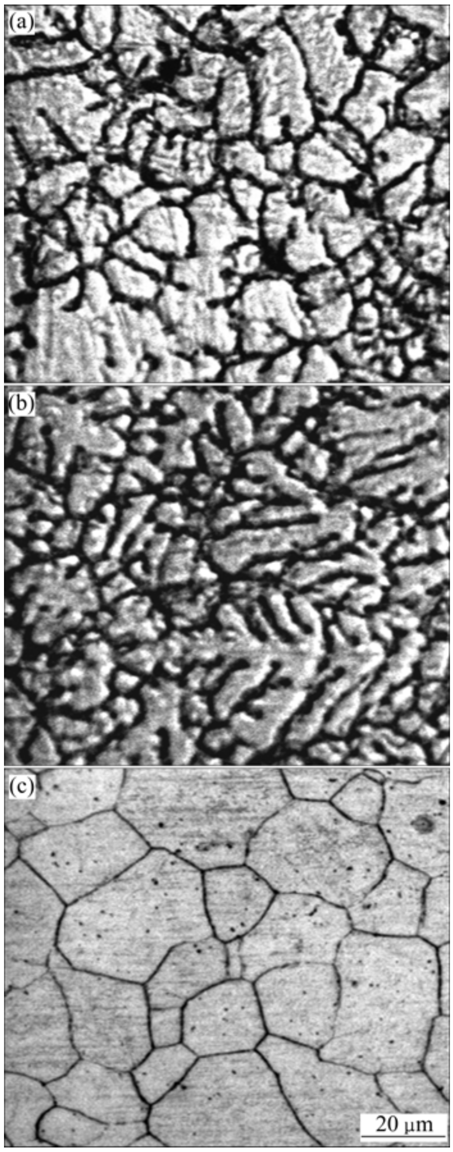


**Fig.9** Microstructures along thickness of cast AZ31 strips with different casting speeds: (a) 10 m/min; (b) 20 m/min; (c) 30 m/min

**Table 2** Mechanical properties of as-cast AZ31 alloy strips after being homogenized for 1 h

| Strip | Casting speed/ $(m\cdot min^{-1})$ | Pouring temperature/K | Strip thickness/mm | Annealing temperature/K | Ultimate tensile strength/MPa | Elongation/ % |
|---|---|---|---|---|---|---|
| A | 10 | 938 | 3.0 | 293 | 149 | 8.17 |
| | | | | 623 | 107 | 9.3 |
| | | | | 673 | 157 | 8.52 |
| | | | | 723 | 159 | 10.32 |
| B | 20 | 923 | 2.1 | 293 | 182 | 8.28 |
| | | | | 623 | 162 | 7.35 |
| | | | | 673 | 169 | 9.48 |
| | | | | 723 | 173 | 11.4 |
| C | 30 | 913 | 1.12 | 293 | 234 | 8.61 |
| | | | | 623 | 235 | 9.34 |
| | | | | 673 | 241 | 12.3 |
| | | | | 723 | 234 | 5.88 |

lower cooling rate. As shown in Fig.9(c), the microstructure of the strip has uniform equiaxed grain in all cross-sections of the strip with the increase of the casting speed.

There is not much difference in the elongation to failure of as-cast strips. Since there are defects in as-cast strips, it should be annealed in order to obtain the favorite performance. After annealing at different temperatures, elongation to failure and tensile strength are both significantly enhanced. By annealing, the non-uniformity in microstructure and composition of as-cast strips are eliminated, thus the plasticity has been improved.

### 3.4 Cold rolling of as-cast products

A cold-rolling test was performed directly after the as-cast AZ31 magnesium sheets were sheared to examine the forming characteristics of the magnesium alloy sheets produced by vertical twin-roll strip casting.

The results show that the as-cast AZ31 magnesium strips can be directly cold rolled with an average deformation of approximately 30% and the maximum deformation of 40%, much larger than that of the conventional magnesium alloy. The cold rolling reduction increases with the decrease of strip thickness in cast-rolled state due to two possible reasons. The first is that the cooling rate of thin strips produced by strip casting is larger than that of thick ones. The second and the possible main reason is that there exist much smaller grains in the thin strips. Generally, the thin magnesium strips obtained by twin-roll casting have relatively uniform equiaxed grain microstructure. Much finer grains render larger grain numbers per unit volume, and the occurrence of deformation in more grains. In addition, grain refining reduces the dislocation slip distance and dislocation piling-up. Therefore, the stress concentration along the grain boundaries is relived, which greatly improves the cold rolling deformation of the thin as-cast magnesium strips.

Through cold rolling, a large number of twins are formed in the deformed microstructure and its dislocation density is so large that the strengths have been greatly improved while plasticity is reduced. Annealing should be carried out to improve the mechanical properties of cold-rolled sheet. In the annealing process, recovery or recrystallization will take place to reduce dislocation density in deformed microstructure and to improve the comprehensive mechanical properties. For AZ31 magnesium alloy, the slip system is so little that the slip of the base plane and cone twin are the main deformation mechanisms in cold deformation. Only those crystal grains that are in the favorable orientations in slipping will deform in priority. But its deformation distribution is uneven in the case of small deformation, and the recrystallization nucleation is not uniform in annealing. The research[16] shows that, for the AZ31 magnesium alloy, the limit of the total deformation is 30% in cold rolling, while the maximum cold-rolled deformation has reached 40% for as-cast magnesium alloy. More recrystallization nucleus will come forth in annealing to obtain grain refinement and uniform distribution. Therefore, its plastic performance will be greatly improved by annealing. The tensile test results for 0.8 mm-thick strip cold rolled and annealed at 350 ℃ for 60 min are given in Fig.10. The UTS value of the strip is 323 MPa after cold rolling and the elongation is 6.3%, whereas the elongation values are increased to more than 23% after annealing.

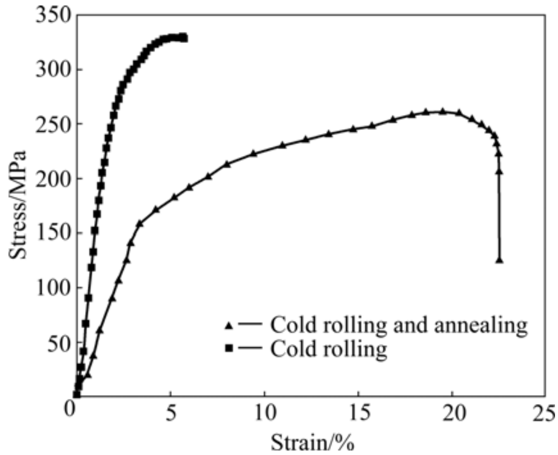


**Fig.10** Engineering stress—strain curves of as-cast AZ31 strips after cold rolling and cold rolling+annealing

Fig.11 shows the microstructures of cold-rolled AZ31 magnesium alloy strips after annealing at 350 ℃ for different time. In general, the solidification structure of magnesium alloy is no longer present due to the technical characteristic of twin-roll casting where the strips can be quickly cooled and solidified under the pressure. The cold-rolled AZ31 magnesium alloy strips annealed at 350 ℃ for 30−60 min have equiaxed crystal structure with an average grain size of 9−10 μm. That is the reason why the mechanical properties of AZ31 strip are greatly improved.

## 4 Conclusions

1) AZ31 magnesium alloy can be successfully manufactured by vertical twin-roll strip casting. The produced strip has a thickness of 1−3 mm and width of 254 mm.

2) It is found that a roll speed of 10−30 m/min and a casting temperature of 640−660 ℃ for AZ31 magnesium alloy are appropriate manufacturing conditions in this experiment.

3) The average grain size of the as-cast AZ31 alloy

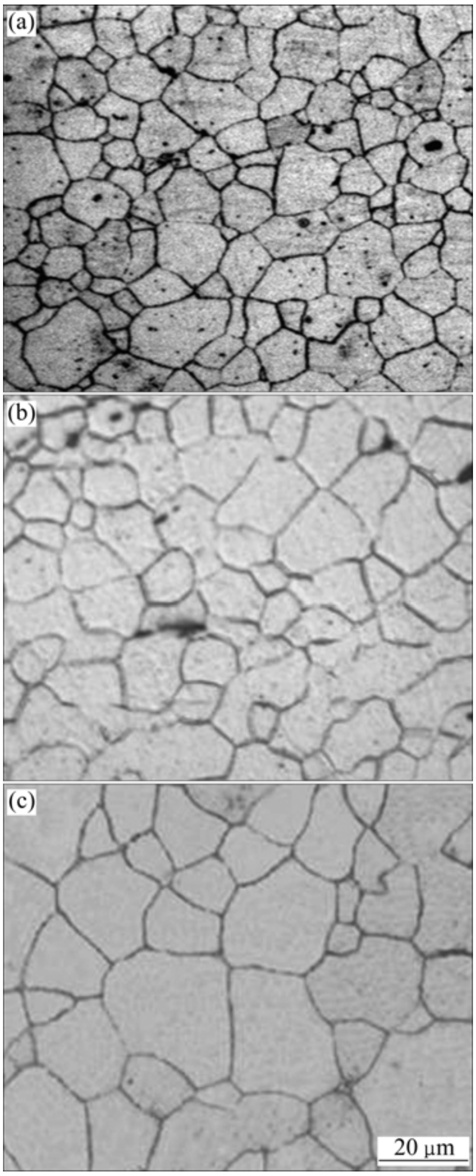


**Fig.11** Microstructural evolution of cold rolled as-cast AZ31 alloy after annealing at 350 ℃ for different time: (a) 30 min; (b) 60 min; (c) 120 min

product is around 22 μm and the as-cast AZ31 magnesium strips have excellent plastic properties. It can also be directly cold-rolled and the maximum cold rolling reduction reaches 40%.

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