Principle of Indentation-flattening compound deformation technology and application in AZ31 Magnesium Alloy

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Abstract: Indentation-flattening compound deformation technology (IFCDT) is defined, and the characteristics and stress-strain state of IFCDT are analyzed. The mechanism of grain refinement and texture weakened of AZ31 magnesium alloy sheet which deformed by IFCDT is analyzed. The influence law of parameters of IFCDT on microstructure and mechanical property of AZ31 magnesium alloy is studied by experiment. The parameters of IFCDT are determined, and the tools of IFCDT are manufactured. It is analyzed that the effect of deformation temperature and reduction ratio on the microstructure and mechanical property of AZ31 magnesium alloy which deformed by IFCDT. The results show that the microstructure and mechanical property of magnesium alloy sheet had been improvement by processed of IFCDT. When deformation temperature is 275 ^{o}C and the reduction ratio is 29 %, and the tools temperature is 150 ^{o}C, the average grain size is 7.84 um, and yield strength is 212 MPa, and tensile strength is 298 MPa, and the elongation ratio reached 17.2 %. Compared with that of ordinary rolling state, the average grain size of IFCDT had been reduced 23 %, and yield strength had been increased 5 %, and tensile strength had been increased 15 %, and the elongation ratio had been increased 4 %, and the hardness had been increased 12 %

1 Introduction

The characteristics of magnesium alloy materials with poor plastic forming ability under normal temperature is limited greatly the development and application. Intense plastic deformation is one of the important methods to produce more twins and more twin slip systems and more dynamic recrystallization, which results to improve the formability of magnesium alloy sheet at room temperature. The texture is weakened and grain is refined. Combined repeating bending process at low temperature and annealing process of AZ31 magnesium alloy, grain is refined effectively, and the base texture is weakened[1]. When magnesium alloy sheet is deformed by one-direction bending technology, the base texture is appeared deflection, and basal texture is weakened[2]. Deformed by wave-shape mold, the forming performance of magnesium alloy sheet improves significantly, and the grain refined to 1.4μm[3]. When AZ31 Mg alloy sheets are deformed by bidirectional cyclic bending, and the grains near the surfaces have full recrystallization, and grain is obviously refined, and the grains in the middle of the sheet just grow up and the texture intensity decreases gradually from the center of the sheet to the surfaces[4]. Under the same condition, the recrystallization at twin boundaries of the forged AZ31 magnesium alloy occurs more easily than that of the compressed AZ31 magnesium alloy [5]. Mg-8Sn-1Al-1Zn alloy indicates high strength and ultrafine grained structure which is deformed by reverse extrusion at 250 ^{o}C. Most of the coarse grains are changed into fine equiaxed size, and average grain sizes is 1.92 μm, and the yield strength is 285 MPa[6]. During the rolling process of magnesium alloy AZ31 tubes, the plastic deformation capability can be improved due to the combination of twinning and slipping, and the optimum tube surface and properties could be obtained when controlling the deformation degree is 11% - 15%[7]. When AZ31 Mg alloy is deformed by integrating forward extrusion, the dynamic recrystallization is induced by the heavily accumulated strains, and the grains are refined and the basal texture is dramatically weakened[8]. At room temperature, with decreasing of grain size, a clear transition from non-basal-slip to basal-slip-dominated flow appears under tension deformation, and a transition from twinning to basal slip takes place under compression deformation. On the other hand, a similar transition from twinning to basal slip takes place with increasing of temperature and decreasing of strain rate[9]. When AZ61 magnesium alloy is deformed by extrusion-forging process, the grain size is refined from 121μm of casting state to 2 - 5μm. From the true stress-strain curves of AZ61 magnesium alloy at room temperature, the tensile strength is 315 MPa, yield strength is 227 MPa and elongation is 20%, which increased by 42%, 76% and 71%, respectively, compared with that of casting state[10].

In this paper, the characteristic and parameters definition of indentation-flattening compound deformation technology (IFCDT) is analysed. It will be researched that the influence law of parameters of IFCDT on microstructure and mechanical properties of AZ31 magnesium alloy.

2 The characteristics of IFCDT

2.1 Definition of IFCDT

Indentation-flattening compound deformation technology (IFCDT) is defined that the plane sheet is deformed by indentation technology (regarded as first deformation process), and then the deformed sheet is deformed by flattening technology continuously (called second deformation), restored the flatness of the deformation sheet. The deformation process is regard as 1 pass of IFCDT. Multi passes of IFCDT can be used to further improve the performance of the material.

The principle of IFCDT is shown as Figure 1(a). Intense tangential deformation can be produced by indentation deformation technology (referred as first deformation), and it can increased the occurrence of dynamic recrystallization of magnesium alloy sheet. More twins and slip system can produce, and it is conducive to the grain refined and basal texture weakened, and the formability of magnesium alloy sheet improved significantly.

The magnesium alloy sheet which is deformed by IFCDT, grain is further refinement, and basal texture is further weakened. The performance and mechanical properties of magnesium alloy sheet improve significantly.

Parameters of IFCDT include deformation temperature (*T*), deformation speed (*V*),the distance of wave (s), the reduction of IFCDT (h), the ratio of deformation (λ=2h/s), which are defined as Figure 1b. The ratio of reduction (Φ) is $\phi = h/t_0$, in which , t0 is the thickness of original sheet. The ratio of reduction (Φ) can describe the composite deformation degree in the thickness direction, and the ratio of deformation (λ) can describe the shear strain strength and deformation zone.

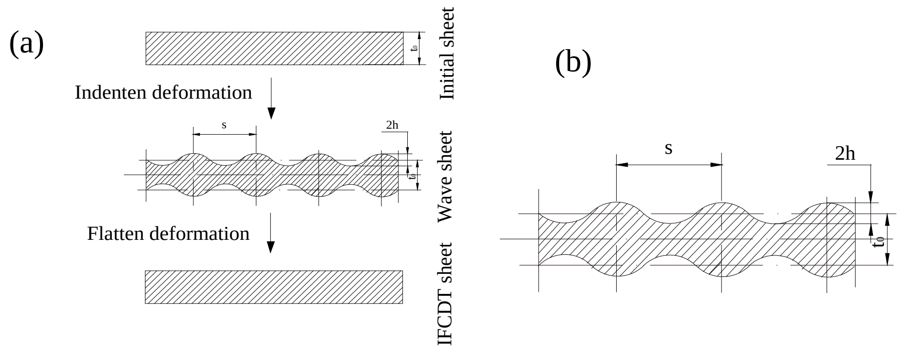

Figure 1 Principle of indentation-flattening compound deformation (IFCDT)(a, principle of IFCDT; b, parameters of IFCDT)

2.2 The stress and strain state of IFCDT

The stress and strain state of deformation zone of indentation deformation technology is shown as Figure 2a. In point P of deformation zone, the stress state is two direction compressive stresses, and the strain at thickness direction is compressive strain. But in point W, the stress state is two direction compressive stresses, and the strain at thickness direction is tensile strain.

The stress and strain state of deformation zone of flattening deformation technology is shown as

Figure 2b. The point P and W is corresponded to Figure 2a. The stress state of point P is two direction compressive stresses, and the strain at thickness direction is tensile strain. But in point W, the stress state is two direction compressive stresses, and the strain at thickness direction is compressive strain.

The strain state in the deformation zone which deformed by IFCDT is changed alternately. The compressive strain is the main factor which produces twins in the magnesium alloy material. Effected alternately by compressive and tensile deformation, the process of microstructure evolution of the deformation of magnesium alloy is that compressive deformation → formation of the twin structure → the dynamic recrystallization → the twin disappearance → the grain refinement.

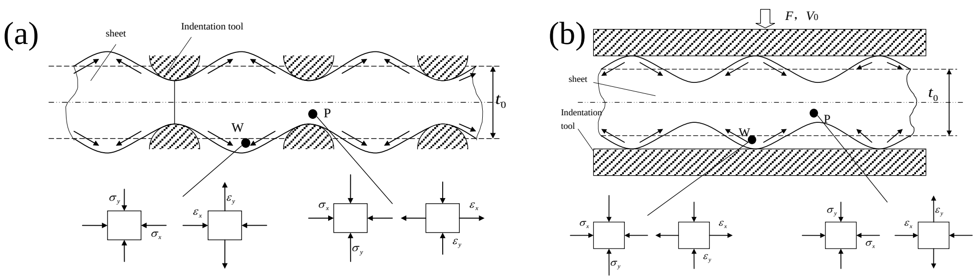

Figure 2 Stress and strain state of IFCDT (a, Indentation deformation; b, Flattening deformation)

2.3 The mechanism of texture weakened

Principle of evolution of grain orientation of AZ31 magnesium alloy sheet which deformed by IFCDT is shown as Figure 3. The complex deformation changes the grain orientation and weakens the texture. The mechanism is that grain orientation vertical (or level) → grain orientation deflection → grain orientation disorder → the texture weakened. Deflection angle of grain orientation changed with the tangential deformation degree. For large tangential deformation degree, the grain deflection angle is 90 degrees. For small tangential deformation degree, the grain deflection angle is less than 90 degrees. When AZ31 magnesium alloy sheet is deformed by IFCDT, the grain orientation will be in a disorder state, and intensity of texture will be reduced, and the texture will be weakened.

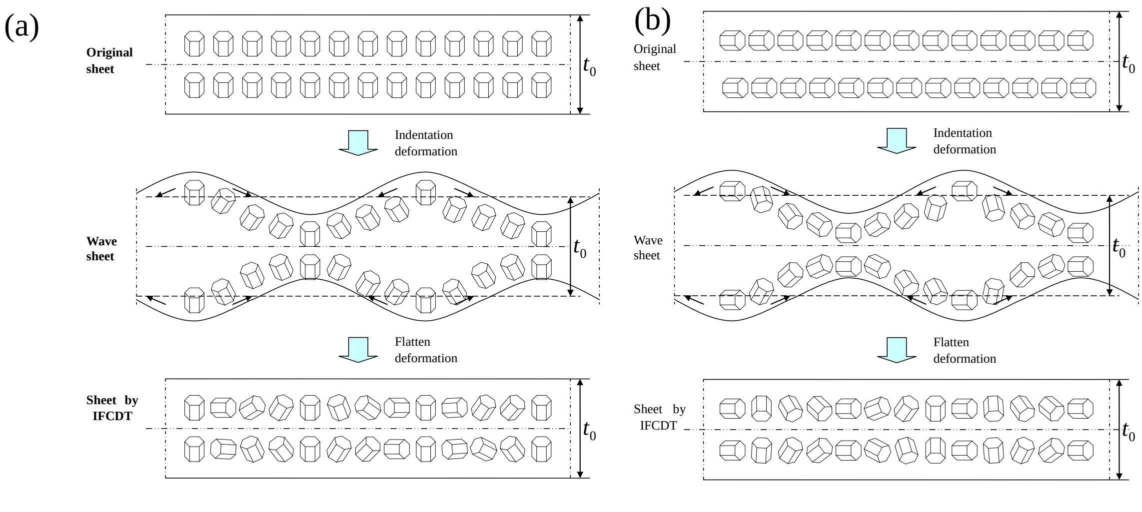

Figure 3 Principle of evolution of grain orientation of AZ31 magnesium alloy sheet deformed by IFCDT(a, Initial grain orientation is thickness direction; b, Initial grain orientation is the rolling direction.)

3 Experiment study

The experimental work is finished in 3150 KN universal hydraulic press. Tools and heating device of experiment study are shown as Figure 4. Electric heating rod is used to heat the tools. The deformation parameters are that the ratio of IFCDT is 1/4, and the reduction ratio is 29%, and the pressing speed is 10 mm/s. The deformation temperature is 225 ^{o}C, 250 ^{o}C, 275 ^{o}C, 300 ^{o}C.

Experimental material is AZ31 magnesium alloy sheet which rolled at high temperature, and the dimension of sheet is 100×200 mm, and the thickness is 7 mm. The uniform annealing process is that the heat temperature being 400 ^{o}C and holding time being 1 h, and then cooling with the furnace.

The surface of the microstructure observation and calculation of grain size are all TD surface (Transverse direction, TD). After annealing process, the microstructure of AZ31 magnesium alloy sheet is uniform, and the average grain size is 25.57 μm, and the yield strength is 169 MPa, and the tensile strength is 248 MPa, and the elongation is 15.6 %.

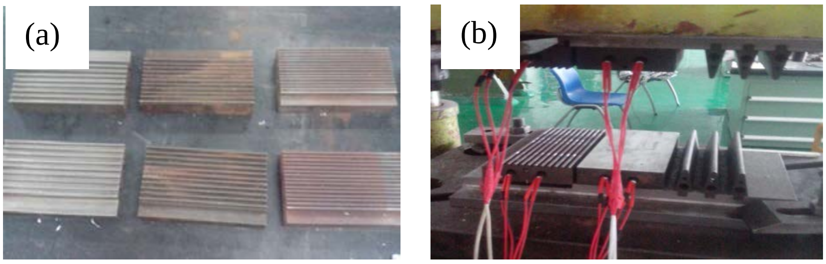

Figure 4 Tools and heating device of IFCDT (a, experiment tools; b, heating device)

4 Analysis of experiment results

4.1 Effect of IFCDT on microstructure of magnesium alloy sheet

When the reduction ratio is 29 %, the effect of deformation temperature on the microstructure of magnesium alloy sheet is shown in Figure 4. When deformation temperature is 225 ^{o}C, 250 ^{o}C, 275 ^{o}C, 300 ^{o}C, the average grain size is 11.35μm, 10.28μm, 7.84μm, 8.56μm, respectively. When the deformation temperature is 225 ^{o}C, cylinder slip and cone slip system is not easy to start at low temperature. The main deformation mechanism is twins, and the recrystallization degree is smaller, and a number of twins exist. With the increasing of deformation temperature, the volume fraction of twins decreases gradually. When the deformation temperature reaches 275 ^{o}C, complete recrystallization is finished, and twins disappeared, and the grain size is small and uniform.

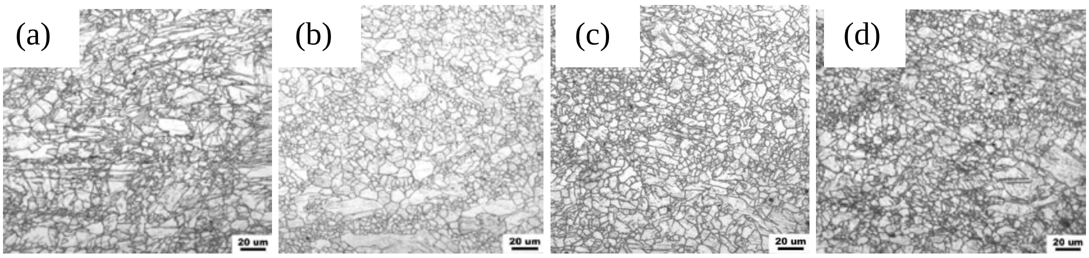

Figure 5 Microstructure at different deformation temperature of AZ31 Mg alloy (reduction ratio 29 %)(a, 225 ^{o}C; b, 250 ^{o}C; c, 275 ^{o}C; d, 300 ^{o}C)

When the deformation temperature is 275 ^{o}C, the microstructure of magnesium alloy sheet at different reduction ratio is shown in Figure 6. When the reduction ratio is 14%, because of the deformation degree being small, recrystallization being not appeared, much twins appeared, and grain distribution is not uniform. When the reduction ratio is 29%, because the twins disappeared gradually and dynamic recrystallization began to appeared, grain size is small and distribution uniformly. When the reduction ratio is 43%, fully dynamic recrystallization appeared, grain size is small and distribution uniformly.

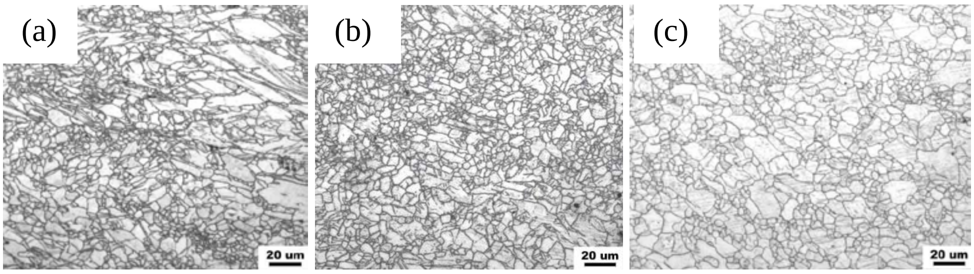

Figure 6 Microstructure at different reduction ratio of AZ31 Mg alloy when deformation temperature is 275 ^{o}C (a, 14 %; b, 29 %; c, 43 %)

4.2 The microstructure and properties of ordinary flat rolling sheet

Ordinary flat rolling process of magnesium alloy sheet is studied by experiment. When deformation temperature is 275 ^{o}C, and the tools temperature is 150 ^{o}C, and the reduction ratio is 29%, the microstructure and mechanical properties of AZ31 magnesium alloy sheet is obtained, shown as Figure 7. The average grain size is 10.13 μm, and yield strength is 203 MPa, and the tensile strength is 259 MPa, and the elongation is 16.5%, and the micro-hardness is 82.47 HV. The properties of magnesium alloy deformed by IFCDT are improved, seen as Table 1. Compared to that of ordinary flat rolling deformation, the properties of magnesium alloy which deformed by IFCDT is increased significantly, which of grain size increased by 23%, yield strength increased by 5%, the tensile strength increased by 15%, the elongation increased by 4%, and the hardness increased by 12%.

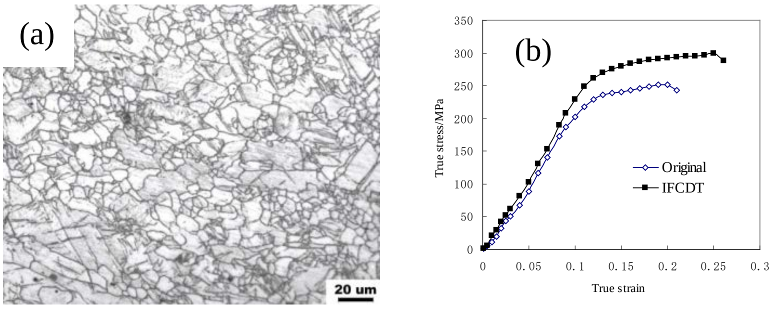

Figure 7 Microstructure and mechanical property of AZ31 Mg alloy deformed by ordinary flat rolling process (a, microstructure; b, curve of stress-strain)

Table 1 Properties of AZ31 Mg alloy sheets with different deformation processes

	Grain size/μm	Micro-hardness /HV	Yield strength /MPa	Tensile strength /MPa	Elongation /%
Original sheet	25.57	54.30	169	248	12.8
Sheet by flat rolled	10.13	82.47	203	259	14.5
Sheet by IFCDT	7.84	91.99	212	298	17.2

5 Conclusions

(1) Indentation-flattening compound deformation technology (IFCDT) is defined, and the characteristics and stress-strain state of IFCDT are analyzed.

(2) The optimal parameters of IFCDT of AZ31 magnesium alloy are that the deformation temperature being 275 ^{o}C, and the reduction ratio being 29%, and the tools temperature is 150 ^{o}C.

The average grain size is 7.84 um, and the yield strength is 212 MPa, and the tensile strength is 298 MPa, and the elongation is 17.2 %.

(3) Compared to that of ordinary flat rolling deformation, the properties of magnesium alloy which deformed by IFCDT is increased significantly, which of grain size increased by 23 %, yield strength increased by 5 %, the tensile strength increased by 15%, the elongation increased by 4 %, and the hardness increased by 12 %.

Acknowledgements

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