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Anisotropy of Mechanical Properties of Magnesium Alloy AZ31 Sheets as a Result of Sign-Variable Bending Deformation

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Hot rolled and annealed at 320 °C AZ31 sheets are featured by low anisotropy of strength (~3 %), significant anisotropy of yield stress (~15 %) and specific elongation (~12 %). Monocrystal adjectives of mechanical properties and the values of those properties in different directions in the plane of sheets, and in the direction perpendicular to the sheet planes after deformation by different number of cycles of sign-variable bending were calculated on the data of mechanical properties measuring in the plane of sheets and the results of X-ray texture analysis in the model of orthorhombic quasimonocrystal.

Keywords: MAGNESIUM, STRUCTURE, TENSOR, BENDING, ANISOTROPY, MONOCRYSTAL ADJECTIVES

Introduction

Structural materials are subjected to sign-variable bending deformation in the process of manufacturing articles and maintenance. Mechanical properties and structure of material change (grain refining, accumulation of defects, structure change, etc.) [1-3].

The principal feature of texture is anisotropy of properties of textured materials. Development of texture and its effect on ductility of AZ31 sheets after sign-variable bending deformation was studied in [3]. However, such approach does not allow quantitative estimation of anisotropy of properties of rolled semi-finished materials.

The task of research is to investigate the textural condition of AZ31 sheets after different sign-variable bending conditions and effect on anisotropy of mechanical properties of sheets.

Results and Discussion

Textured metal sheet can be considered as a quasimonocrystal of trimetric symmetry with axes aligned with rolling direction (RD), crosswise direction (CD) and direction perpendicular to the sheet plane (PD). For metal sheet, anisotropy of properties of fourth tensor dimension is defined by constants of quasimonocrystal s_{ijkl}^{QM} and trigonometrical functions setting the direction of interest [4]. The constants s_{ijkl}^{QM} can be determined by averaging of monocrystal constants in the system of coordinates of sample (sheet) on all possible orientations of crystals.

Averaging can be carried out by any weight function which reflects the orientational distribution of crystals in any space or its crystallographic directions. Transition from system of coordinates of crystal to that of sample is accomplished by the known law [6]:

$$s'_{ijkl} = \alpha_{ij}\alpha_{ik}\alpha_{kl}\alpha_{jl}s_{ijkl} \quad \text{(Eq. 1)}$$

where S_{ijkl} - monocrystal constants in the system of coordinates of crystal, α_{mn} -directing cosines of direction. For hexagonal crystals, it is convenient to select axis *c* as such direction and to use weight function for averaging. This function is simple enough to obtain from a pole figure (0002) constructed by to X-ray texture analysis data [5].

$$s_{ijkl}^{QM} = \int_0^{2\pi}\int_0^{\pi} s'_{ijkl}(\alpha,\beta) P_{(0002)}(\alpha,\beta)\sin\alpha\cdot d\alpha\ d\beta \qquad \text{(Eq. 2)}$$

where α and β - azimuth and meridional angles, $\sin\alpha\cdot d\alpha\ d\beta$ - area element in space polar coordinates.

When calculating s_{ijkl}^{QM}, it is possible to select the combinations of directional cosines

$$I_1 = \langle\alpha_{13}^2\rangle, I_2 = \langle\alpha_{23}^2\rangle, I_3 = \langle\alpha_{33}^2\rangle,$$
$$I_4 = \langle\alpha_{13}^4\rangle, I_5 = \langle\alpha_{23}^4\rangle$$
$$I_6 = \langle\alpha_{13}^2\alpha_{23}^2\rangle \qquad \text{(Eq. 3)}$$

which contain comprehensive information about distribution of crystals on orientations in a polycrystallic body. Sign $\langle\ \rangle$ means averaging on all orientations of crystals. They were called integral characteristics of texture in [6]. There are only 5 integral characteristics of texture for flat (sheet) textures of hexagonal metals and alloys, though 6 integral characteristics of texture are used for convenience of calculation of elastic anisotropy [6] keeping in mind that:

$$\left(I_1^{(h)} + I_2^{(h)} + I_3^{(h)}\right) = 1 \qquad \text{(Eq. 4)}$$

3 integral characteristics of texture are enough to describe anisotropy of properties of second tensor dimension:

$$\Re(\varphi) = \Re_1^{QM} + \left(\Re_1^{QM} + \Re_2^{QM}\right)\cos^2\varphi \qquad \text{(Eq. 5)}$$

$$\Re_1^{QM} = \rho_1^{(M)} + \left(\rho_2^{M} - \rho_1^{(M)}\right)I_1,$$
$$\Re_2^{QM} = \rho_2^{(M)} + \left(\rho_2^{(M)} - \rho_1^{(M)}\right)I_2 \qquad \text{(Eq. 6)}$$

where $\Re_i^{QM}(\varphi)$ - property in the sheet plane in direction (RD+φ), ρ_1^M, ρ_2^M - monocrystal properties, I_i – integral characteristics of texture.

Value of second tensor dimension property in the direction perpendicular to the sheet plane is expressed by the following formula [7]:

$$\Re_{ND}^{QM} = \rho_1^M + (\rho_2^M - \rho_1^M)I_3 \qquad \text{(Eq. 7)}$$

If accept property values measured in rolling direction and crosswise direction $\Re_1^{QM} = \Re(0)$; $\Re_2^{QM}\left(\frac{\pi}{2}\right)$ as $\Re_1^{QM}$ and $\Re_2^{QM}$, monocrystal adjectives will be:

$$\rho_1^M = \frac{\Re_1^{QM}(1+I_2) - \Re_2^{QM} I_1}{1 + I_2 - I_1},$$
$$\rho_2^M = \frac{\Re_2^{QM}(1-I_1) + \Re_1^{QM} I_2}{1 + I_2 - I_1} \qquad \text{(Eq. 8)}$$

Hot rolled to 1.07 mm and annealed during half an hour at 320 °C AZ31 sheets were test materials. Plates with dimensions 100×100 mm were cut out from sheets and subjected to sign-variable bending deformation in rolling direction in 1, 2, 4, 6 and 8 cycles on rollers with diameter 50 mm in the direction aligned with rolling direction.

Disklike specimens were cut out from initial sheet and plates subjected to sign-variable bending deformation for X-ray diffraction research, and square-angled specimens with dimensions 10×100 mm were cut out from initial sheet at different angles to rolling direction in order to measure anisotropy of mechanical properties. Mechanical properties were estimated by results of tensile test on INSTRON. Deformed layer (~0.1

mm) was removed by etching. Polar density curves were recorded by Schultz's method on diffractometer DRON-3M for plane (0002) in CuK $_{\alpha}$ radiation within tilt angles α = 0 - 70 ° of sample to goniometer axis. Values of polar density in peripheral area of pole figure were nulled. Pole figures of AZ31 sheets after hot rolling and recrystallization annealing and after further deformation by three cycles are resulted in [3], and pole figures of texture at depth of ~ 0.2 mm after one and eight cycles of sign-variable bending are shown in **Figure 1**.

The texture of sheets subjected to sign-variable bending deformation by 4, 6 and more cycles differs slightly from those deformed by 1-2 cycles. Spread of crystal orientation in rolling direction and polar density in the centre of pole figure increase, areas with raised polar density in crosswise direction at angles 40-60 ° appear, polar density in the area corresponding to orientation (0001) ± α PD-RD weakens a little. Such texture development was explained in [3] by the fact that there was intensive twinning in surface layers and near the surface at early stages of sign-variable bending deformation. At further sign-variable bending deformation, slip systems become active and are aimed to move poles [0001] in the centre of pole figure until the dynamic equilibrium between all acting systems of large deformation. And statistic tilt angle of hexagonal prism to sheet plane calculated from condition $\sin^2\alpha = \left|I_2^{(h)} - I_1^{(h)}\right|$ varies nonmonotonely. If this angle is ~6-7 ° in the initial state, it will increase to 12-14 ° after one cycle of sign-variable bending and further it will be on the level ~10 °.

Integral characteristics of texture during sign-variable bending deformation of AZ31 plates were calculated by equation 1. Results are presented in **Table 1**.

Experimental values of yield stress and tensile strength σ_{YS}, σ_{TS} for three directions in АЦ31 sheets after hot rolling and annealing at 320 °C, in RD, RD+45 ° and CD were 170; 178; 200 MPa and 260; 263; 268 MPa respectively, and elongation δ in the same directions: 27.8; 27 and 25.6 %. Mechanical properties are represented in **Figure 2**. Anisotropy of AZ31 sheets mechanical properties is featured by two-fold symmetry and well approximated by Fourier's series containing an absolute term and quadratic component. It allows modeling anisotropic sheet of AZ31 alloy by quasimonocrystal of trimetric symmetry.

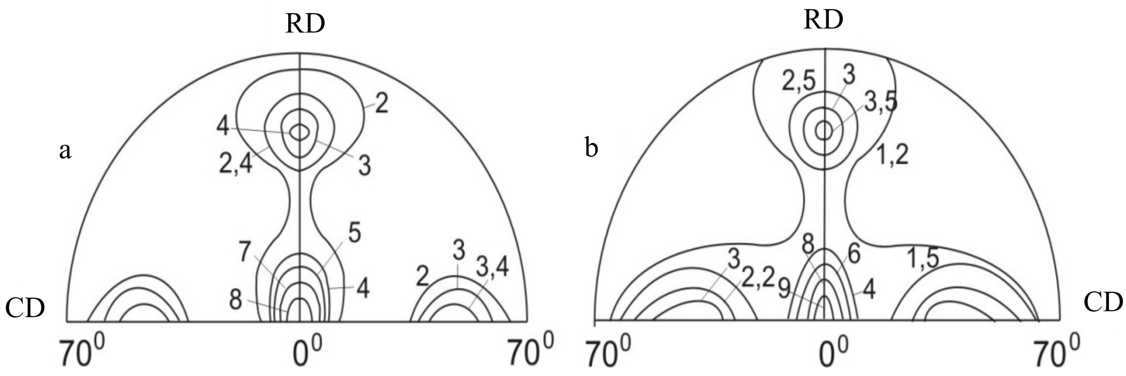

Figure 1. Pole figures (0002) of AZ31 sheets after deformation: *a* - 1 cycle; *b* - 8 cycles of sign-variable bending

Table 1. Values of integral characteristics of AZ31 plates texture after different types of sign-variable bending deformation

Number of sign-variable bending cycles	Integral characteristic of texture, I_i					
	I_1	I_2	I_3	I_4	I_5	I_6
Initial	0.19864	0.16723	0.6331	0.115	0.858	0.00023
1 cycle	0.2188	0.1789	0.6022	0.1178	0.1046	0.00042
2 cycles	0.2299	0.2171	0.5529	0.1234	0.12805	0.00036
4 cycles	0.2194	0.2086	0.5719	0.11708	0.1238	0.00044
6 cycles	0.2201	0.2021	0.5779	0.11808	0.1218	0.00045
8 cycles	0.2243	0.19607	0.5796	0.1194	0.1195	0.00042

Values of AZ31 monocrystal adjectives in the initial state (hot rolling and recrystallization annealing at 320 °C) were: for yield stress σ_{YS1} = 163.8 and σ_{YS3} =1 94.8 MPa, for tensile strength σ_{TS1} = 258.2 and σ_{TS3} = 266.5 MPa, for elongation δ_1 = 28.3 and δ_3 = 26.0 %.

Values of mechanical properties in rolling direction RD, crosswise direction CD and direction perpendicular to the sheet plane PD were calculated for sheets deformed by sign-variable bending. The results are summarized in **Table 2** and **Figure 3**. Sheets are significantly anizotropic in the initial state by values of yield stress and specific elongation. Anisotropy factors for these properties in the initial sheets were 15 and 12 % for σ_{YS} and δ respectively. Anisotropy of σ_{TS} is ~3 % and its values remain at the constant level with increase of number of sign-variable bending deformation cycles, which was mentioned in [1, 2]. Yield stress and elongation tend to drop in rolling direction. In crosswise direction, σ_{YS} decreases as well, and δ decreases after one pass by cold straightening (i.e. in the field of the most intensive textural transformations caused by twinning), and further it is stabilized at the initial level. δ behaves in the same way in direction RD+45 °.

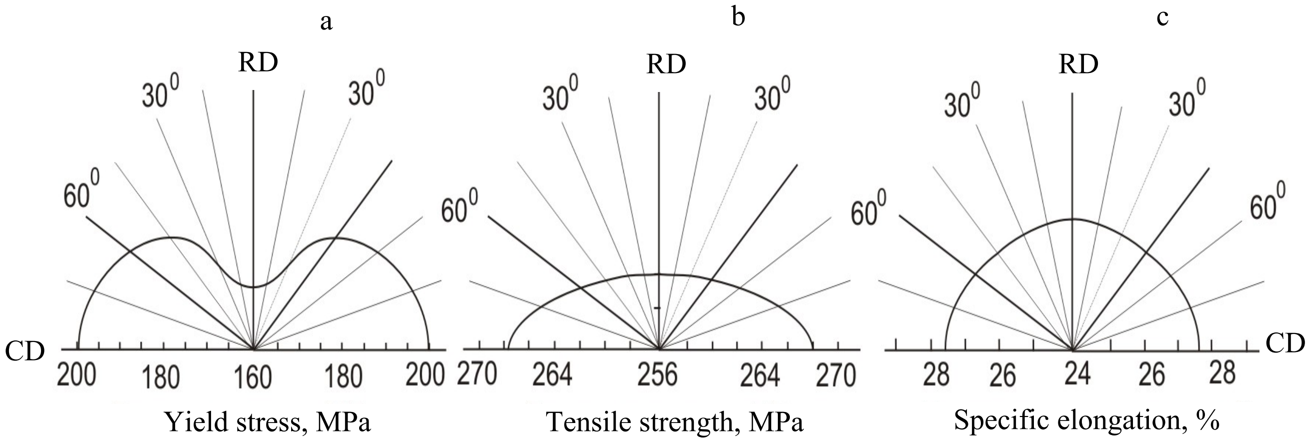

Figure 2. Anisotropy of yield stress (*a*), tensile strength (*b*), specific elongation (*c*) of AZ31 sheets after hot rolling and recrystallization annealing

Table 2. Values of mechanical properties in different directions of AZ31 sheets subjected to sign-variable bending deformation

Number of sign-variable bending cycles	Mechanical properties								
	σ_{TS}, MPa			σ_{YS}, MPa			δ		
	Direction of property measurement								
	RD	CD	PD	RD	CD	PD	RD	CD	PD
0	170.0	200.0	183.4	260	268.0	263.6	27.8	25.6	26.8
1	169.0	214.4	190.2	259.7	271.8	265.4	27.8	24.5	26.3
2	170.9	201.5	180.9	260.3	268.4	262.9	27.7	25.5	26.9
4	170.6	201.3	181.5	260.2	268.3	263.1	27.7	25.5	26.9
6	170.6	201.1	181.7	260.2	268.3	263.1	27.8	25.5	26.9
8	170.8	200.9	181.8	260.2	268.2	263.1	27.7	25.5	26.9

Conclusions

1. The most noticable change of mechanical properties is observed after the first cycle of sign-variable bending.

2. Deformation of AZ31 sheets by sign-variable bending forms a texture with statistical tilt angle of hexagonal prism in rolling direction ~ 10-14 ° and with maximum after one cycle of sign-variable bending.

3. Integrated characteristics of texture contain information about anisotropy of properties of rolled sheet of hexagonal metals and alloys and can be used for certification of sheet materials by textural parameters.

4. Monocrystal adjectives, anisotropy of tensile strength, yield stress and specific elongation in the plane of sheets and their values in the direction perpendicular to the sheet plane for different number of sign-variable bending deformation cycles were defined by results of experimental anisotropy of mechanical properties in the plane of AZ31 sheets.

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Анизотропия механических свойств листов магниевого сплава AZ31 в результате деформации знакопеременным изгибом

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Листы сплава AZ31 после горячей прокатки и отжига при 320^0 обладают низкой анизотропией предела прочности (~3%), значительной анизотропией предела текучести (~15%) и относительного удлинения (~12%). По результатам измерения механических свойств в плоскости листов и результатов рентгеновского текстурного анализа в модели орторомбического квазимонокристалла рассчитали монокристальные характеристики механических свойств сплава и значения свойств для разных направлений в плоскости листов и в направлении, нормальном к плоскости листов для различного числа циклов деформации знакопеременным изгибом.