

Influence of Material Structure Crystallography on its Formability in Sheet Metal Forming Processes

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Abstract. The finite element simulation was used to analyze the effect of crystallographic texture on material formability in typical sheet metal forming processes: stretch forming, hole expansion, drawing and bending. It is defined that the best formability (maximum cupping depth, flanging ratio, drawing depth, minimum bending radius) is provided by a rotated cube orientation; the worst – by Goss orientation. Some texture components provide better formability than the isotropic case (rotated cube), some - worse (cube, goss) or close to isotropy (copper, brass or S-orientation).

1. Introduction

It is well known that such widespread in the aerospace industry semi-finished products like sheets, bars, extrusions, tubes, etc. possess a pronounced anisotropy of properties. Ignoring the anisotropy in technological calculations not only reduces the expected limit strains of the blanks, but also leads to a number of other undesirable phenomena: increased metal consumption, distortion of shape and size, decrease of finished part performance [1-6]. On the other hand, rational anisotropy is a serious factor for the intensification of the metal forming processes and improvement of the parts performance in certain directions [6-11].

The optimal anisotropy of properties for a particular metal forming process can be determined by means of computer simulation, the modern development level of which allows transferring a significant part of the work on the evaluation and analysis of the stress-strain state to the area of numerical experiment, receiving a great amount of information; implementing a comprehensive study not only of the forming processes, but also of the material behavior depending on its structure; considering and comparing a great number of alternatives [12-14].

The plasticity criterion developed in [15] allows taking into account the crystallographic texture and formulating requirements to it. The peculiarity of the mentioned above criterion is that it explicitly includes the parameters of the crystallographic orientation and the crystal lattice constants. On the basis of this criterion, a material model was developed [16], which made it possible to perform an analysis of the metal forming processes taking into account the crystallographic orientation of the blanks structure [17-18].



Using this material model, the influence of the crystallographic orientation of the structure on material formability in various sheet metal forming operations (stretch forming, drawing, bending, flanging) has been studied.

2. Numerical Simulation

Figure 1 shows the finite element models of the sheet metal forming processes under consideration. The dimensions and geometry of the models correspond to the standard tests for stretch forming (ISO 20422), hole expansion (ISO 16630), earing (EN 1669) and variable-radius bending [19]. In all cases, the blank thickness is 1 mm. Finite element models are made using 4-node shell elements with 5 integration points over the thickness. In order to reduce the number of elements, quarter of the volume was modeled (for bending – half). Between the tool and the blank contact pairs were prescribed, the friction on which obeys the Coulomb law (the friction coefficient is assumed to be 0.12). The tool was taken absolutely rigid.

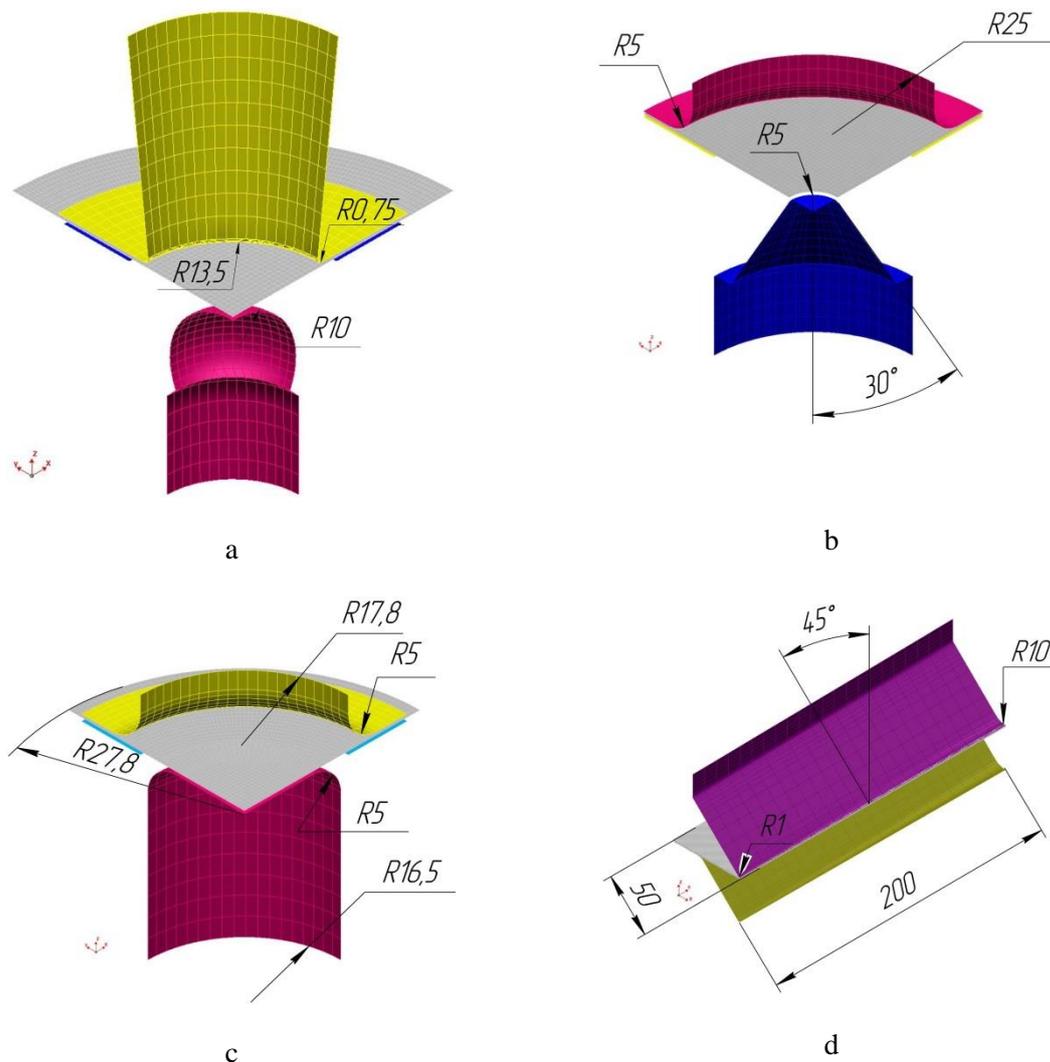


Figure 1. Finite element models: a – stretch forming; b – hole expansion; c - drawing; d - bending with variable radius

The model of orthotropic elasto-plastic material considering crystallographic texture is used to describe the blank material behavior - high-strength aluminum-lithium alloy V-1461 [15]:

$$\sigma_i = \sqrt{\frac{\eta_{12} + \eta_{31}}{2} \cdot \sigma_{12}^2 + \frac{\eta_{12} + \eta_{23}}{2} \cdot \sigma_{22}^2 - \eta_{12} \sigma_{11} \sigma_{22} + (5 - 2\eta_{12}) \sigma_{12}^2} \quad (1)$$

Here σ_i is the equivalent stress; σ_{ij} is stress tensor. The generalized anisotropy parameters η_{ij} are defined by:

$$\eta_{ij} = 1 - \frac{15(A'-1)}{3+2A'} \left(\Delta_i + \Delta_j - \Delta_k - \frac{1}{5} \right) \quad (2)$$

where A' is the anisotropy parameter of the crystal lattice; Δ_i are the orientation factors of crystallographic orientation:

$$\Delta_i = \frac{h_i^2 k_i^2 + k_i^2 l_i^2 + l_i^2 h_i^2}{(h_i^2 + k_i^2 + l_i^2)^2} \quad (3)$$

h_i, k_i, l_i are Miller indices defining the i -th direction in the crystal with respect to the coordinate system associated with the blank. Rolling direction is set along the axis X (for bending test – along bending line).

Material hardening during plastic deformation obeys the Swift's law [20]:

$$\sigma_i = k(\varepsilon_0 + \varepsilon_i)^n \quad (4)$$

where ε_i is the equivalent strain; ε_0 is the initial strain of plastic flow; n is the hardening exponent; k is the hardening coefficient. The strain ε_0 , at which the material changes from elastic to plastic state, has been found by equaling the Eq. (4) and Hooke's law ($\sigma = E\varepsilon$, here E is the Young's modulus). Properties of V-1461 aluminum alloy are given in table 1.

Table 1. The properties of alloy V-1461

Parameter	Value
Young Modulus, E (GPa)	79.5
Puasson coefficient	0.33
Density, ρ (kg/m ³)	2.6
Hardening coefficient, k (GPa)	0.7091
Hardening exponent, n	0.01627
Initial strain of plastic flow, ε_0	0.102

In order to assess the influence of structure crystallography on the formability it was modeled anisotropic material, the texture of which is represented by only one ideal crystallographic orientation. It was considered the most characteristic for the rolled material deformation orientations (copper {112} <111>, brass {110} <112>, S {123} <634>, rotated cube {100} <011>) and recrystallization orientations (cube {100} <001> and Goss {110} <001>) [21]. The orientation parameters are given in table 2. In the calculations it was assumed that for aluminum-lithium alloys $A' = 2.05$ [22].

To determine the formability of the material during the forming process, the following fracture criterion was used [17]:

$$\psi = \frac{\varepsilon_i}{\varepsilon_i^{lim}} < 1 \quad (5)$$

Table 2. Crystallographic orientations and their parameters.

Name	Orientation Designation	Generalized anisotropy parameters		
		η_{12}	η_{23}	η_{31}
Copper	{112}<111>	0.705	1.073	0.705
Brass	{110}<112>	0.705	0.705	1.073
S	{123}<634>	0.758	0.896	0.882
Rotated cube	{100}<011>	0.335	1.444	1.444
Cube	{100}<001>	1.444	1.444	1.444
Goss	{110}<001>	1.444	0.335	1.444
Isotropy		1	1	1

where ε_i^{lim} is the limit strain, which depends on the stress-strain state and the material texture. So ε_i^{lim} for stretch forming and hole expansion was calculated by the next formula:

$$\varepsilon_i^{lim} = \frac{K}{(\eta_{12} + \eta_{31}) - \eta_{12}m} n \quad (6)$$

for drawing:

$$\varepsilon_i^{lim} = \frac{K}{(\eta_{12} + \eta_{23})m - \eta_{12}} n \quad (7)$$

where $K = \sqrt{2} \sqrt{(\eta_{12} + \eta_{31}) - \eta_{12}m + (\eta_{12} + \eta_{23})m^2}$, and $m = \sigma_{11}/\sigma_{22}$ is the stress state index.

3. Results and discussion

Tables 3 and figure 2 show the parameters of the stretch forming, hole expansion, drawing and bending processes at the moment of fracture initiation ($\psi = 0.9$). It is evident that the maximum formability of the material (maximum cupping depth, flanging ratio, drawing depth, minimum bending radius) is provided by an ideal crystallographic orientation {100} <011>; the minimum – by orientation {110} <001>. Some texture components provide better formability in comparison with the isotropic case ({100} <011>), some worse ({100} <001>, {110} <001>) or close to isotropy ({112} <111>, {110} <112>, {123} <634>).

Table 3. Limiting parameters of the sheet metal forming process depending on the crystallographic orientation

Orientation	Process/ parameter		
	Stretch forming	Hole expansion	Drawing
	Cupping depth (mm)	Flanging ratio	Drawing depth (mm)
{112}<111>	5.3	1.244	9.4
{110}<112>	5.0	1.260	9.8
{123}<634>	5.1	1.208	9.55
{100}<011>	6.05	1.420	10.35
{100}<001>	4.35	1.108	6.55
{110}<001>	4.6	1.059	5.3
Isotropic	5.05	1.154	9.55

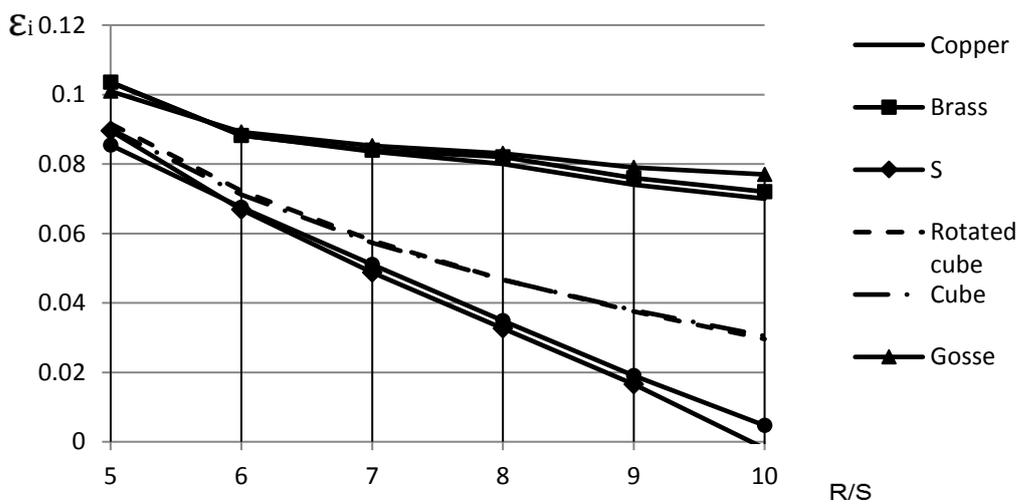


Figure 2. Dependence of the equivalent strain on the relative bending radius

Thus, when developing the thermomechanical conditions of production sheets from aluminum alloys, including aluminum-lithium, it is necessary to assign consistent rolling and intermediate heat treatment (annealing) conditions, since only a combination of various ideal crystallographic orientations of deformation and recrystallization types can provide an increase in formability in sheet forming technological processes. Upon that, the composition of the texture components will be individual for each specific forming process.

4. Conclusion

The proposed calculation procedure considers the crystal lattice constants and the parameters of crystallographic orientation of material. The main practical significance of this procedure is possibility to predict the effect of crystallographic texture of rolled sheets on limiting strains and formability of material in different metal forming process. In addition, the proposed procedure allows designing the composition of crystallographic texture depending on the requirements of the metal forming processes.

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