ANISOTROPIC BEHAVIOUR OF ALUMINIUM ALLOYS SHEETS

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ABSTRACT: Biaxial tensile deformation tests were carried out on cruciform specimens using a CNC stretch-drawing facility designed and built at the Institute for Metal Forming Technology, Stuttgart University. The beginning of plastic yield was monitored by temperature measurements according to the method of Sallat. The observed plastic anisotropy was modeled using the phenomenological yield criteria (Hill'48, Hill'90, Barlat'91 and BBC2000). In Banabic et al anisotropy is introduced by a means of a linear transformation of the Cauchy stress tensor applied to the material. Comparison with experimental data show that the BBC2000 criterion can successfully describe anisotropy of both the plastic strain ratio and yield of aluminum alloys.

KEYWORDS: yield criterion, anisotropy, plane stress , aluminium alloy

1. INTRODUCTION

For computer simulation of sheet metal forming processes, a quantitative description of plastic anisotropy by the yield locus of the material is required. For taking into account the anisotropy, the von Mises classical yield criterion has been modified. A simple approximation for this purpose is given by the quadratic Hill criterion [1]. Later on, several scientists have proposed more and more sophisticated yield functions for anisotropic materials. Hill himself successively improved his criterion in 1979 [2], 1990 [3] and 1993 [4]. Another important research direction in the field was initiated by Hosford [5] who introduced an isotropic yield function, based on the results of polycrystal calculations. This criterion was later generalized to anisotropic materials in plane stress conditions [6] and finally yield functions emerged for any complex stress state [7, 8]. During the last two decades, a lot of yield functions were introduced in order to improve the fitting of the experimental results. Thus: Barlat and Richmond [7] introduced a new non-quadratic function, including the shear stress components (extended by Barlat and Lian [8] for anisotropic case); Barlat et al. [9] has developed a six-component yield function, by using a linear transformation of the stress state (extended by Barlat et al. [10, 11]); Karafillis and Boyce [12] have generalized the Barlat criterion [9] using a "weighted" linear transformation; Barlat et al [13] and Banabic et al [14, 15] have introduced, independently, new plane stress yield functions using the linear transformations only on the Cauchy stress tensor; Cazacu and Barlat developed an orthotropic yield criterion based on Drucker yield function [16]. Vegter et al [17] has proposed the representation of the yield function with the help of Bezier's interpolation using directly the test results. The Casteljau's graphical procedure and the biaxial anisotropy coefficient has been used by Pöhlandt, Banabic and Lange [18] to improve the accuracy of yield criteria. A comprehensive review of anisotropic yield criteria is presented in the Banabic's book [19].

2. NEW YIELD CRITERION FOR ORTHOTROPIC SHEET METALS

A yield surface is generally described by an implicit equation of the form

$$\Phi\left(\overline{s}, Y\right) := \overline{s} - Y = 0 \qquad (1)$$

where $\overline{s}$ is the equivalent stress and Y is a yield parameter.

The equivalent stress is defined by the following relationship:

$$\overline{s} = \left[a(b\Gamma + c\Psi)^{2k} + a(b\Gamma - c\Psi)^{2k} + (1-a)(2c\Psi)^{2k}\right]^{\frac{1}{2k}} \quad (2)$$

where a, b, c, and k are material parameters, while G and ? are functions of the second and third invariants of a fictitious deviatoric stress tensor **s'** which will be described later on. One may notice that the above expression of the equivalent stress is derived from the one proposed by Barlat and Lian for orthotropic materials under plane-stress state [8]. Two additional parameters, namely b and c, have been introduced in order to allow a better representation of the plastic behaviour of the sheet metal. The convexity of the yield surface described by Eqns (1) and (2) is ensured if a $\in$ [0, 1] and k is a strictly positive integer number.

As we have already mentioned, G and ? are functions of the second and third invariants of a fictitious deviatoric stress tensor **s'**. This tensor is related to the actual stress tensor **s** by the Karafillis-Boyce linear transformation [12]:

$$\begin{aligned} &s'_{11} = ds_{11} + es_{22}, \quad s'_{22} = es_{11} + fs_{22}, \quad s'_{33} = -(d+e)s_{11} - (e+f)s_{22}, \\ &s'_{12} = gs_{12}, \quad s'_{21} = gs_{21}, \quad s'_{23} = s'_{32} \equiv 0, \quad s'_{31} = s'_{32} \equiv 0 \end{aligned} \quad (3)$$

where d, e, f, and g are also material parameters. The components of the stress tensors in Eqns (3) are expressed in the system of orthotropic axes (1 is the rolling direction - RD, 2 is the transverse direction - TD, and 3 is the normal direction - ND).

The second and third invariants of the deviatoric tensor **s'** have the following expressions:

$$J'_2 = (s'_{gg})^2 - \det s'_{ab}, \quad J'_3 = -(\det s'_{ab})s'_{gg} \quad (4)$$

where the Greek indices take the values 1 and 2. The quantities

$$I'_2 = s'_{gg}, \quad I'_3 = \det s'_{ab} \quad (5)$$

are not affected by the rotations that leave unchanged the third axis (ND). Thus, in the case of the plane-stress of sheet metals, we can use I'_2 and I'_3 instead of J'_2 and J'_3 in order to define the functions G and ? . We have adopted the following expressions for these functions:

$$\Gamma = I'_2, \quad \Psi = \left[\left(\frac{I'_2}{2}\right)^2 - I'_3\right]^{\frac{1}{2}} \quad (6)$$

By using Eqns (3), (5) and (6), we can express G and ? as explicit dependencies of the actual stress components:

$$\Gamma = Ms_{11} + Ns_{22}, \quad \Psi = \sqrt{(Ps_{11} + Qs_{22})^2 + Rs_{12}s_{21}} \quad (7)$$

The procedure used for identifying the parameters a, b, c, M, N, P, Q, R is described in §2.2 (see more details in ref. [14, 15]. From these parameters, k has a distinct status. More precisely, its value is set in accordance with the crystallographic structure of the material [6]: k = 3 for BCC alloys, and k = 4 for FCC alloys.

2.2. Identification procedure

The parameters a, b, c, M, N, P, Q, R in the expression of the equivalent stress are established in such a way that the constitutive equation associated to the yield surface reproduce as well as possible the following experimental characteristics of the orthotropic sheet metal: s_0^{exp}, s_{90}^{exp}, s_{45}^{exp}, s_b^{exp}, r_0^{exp}, r_{90}^{exp} and r_{45}^{exp}. There are as many conditions as the material parameters in the expression of the equivalent stress. Thus it is possible to obtain their values by solving a set of seven non-linear equations. But this is a difficult approach, because the set of equations has multiple solutions. After several trials and comparisons with experimental data, we have concluded that the best solution is to avoid the strict enforcement of the restrictions mentioned above. A more effective strategy of identification is to impose the minimization of the following error function:

$$F(a,b,c,M,N,P,Q,R)=\left(\frac{\sigma_0}{\sigma_0^{exp}}-1\right)^2+\left(\frac{\sigma_{90}}{\sigma_{90}^{exp}}-1\right)^2+\left(\frac{\sigma_{45}}{\sigma_{45}^{exp}}-1\right)^2+$$
$$\left(\frac{\sigma_b}{\sigma_b^{exp}}-1\right)^2+\left(\frac{r_0}{r_0^{exp}}-1\right)^2+\left(\frac{r_{90}}{r_{90}^{exp}}-1\right)^2+\left(\frac{r_{45}}{r_{45}^{exp}}-1\right)^2 \quad (9)$$

where σ_0, σ_{90}, σ_{45}, σ_b, r_0, r_{90}, and r_{45} are the uniaxial yield stresses, the equi-biaxial yield stress and the coefficients of plastic anisotropy predicted by the constitutive equation. The prediction of uniaxial and biaxial yield stresses and of anisotropy coefficients are presented in the papers [14,15].

3. EXPERIMENTAL PROCEDURE

By varying the longitudinal and transverse force acting on a cruciform tensile specimen any point of the yield locus in the range of biaxial tensile stress can be realized. Kreissig [20] described a cross tensile specimen which has been optimised [21] (Figure 1). In order to determine the yield loci of materials in the initial state without pre-straining, the nominal cross section from the workshop drawing can be used with good accuracy. All the yield loci presented below have been calculated in this way. The typical characterization of the yield surface is made using five experimental points under seven different ratios of the applied stresses: 1:0, 4:1, 2:1, 1:1, 1:2, 1:4, 0:1. As σ_0, σ_{90} and σ_b are used in the identification of the yield criterion, the two other points will be used to make the difference. All these points are in the first quadrant (biaxial tension). The beginning of plastic yield was monitored by temperature measurements according to the method of Sallat [22]. The temperature of the specimen was measured by an infrared thermo-couple positioned at an optimised distance from the specimen. During elastic straining, the specimen's temperature decreases by a

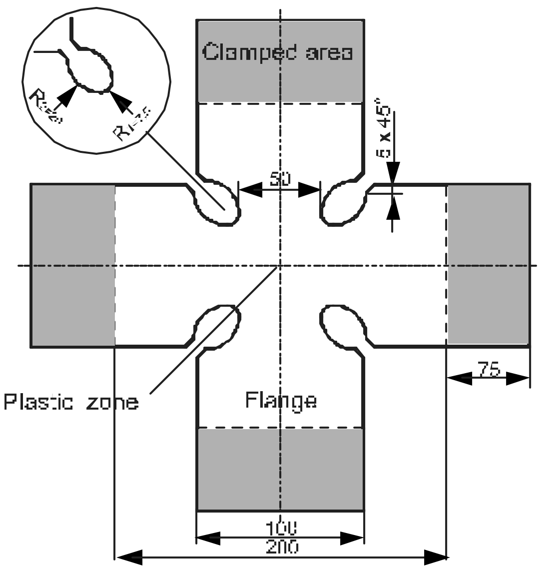

Fig. 1. Cruciform specimen for the biaxial tensile test

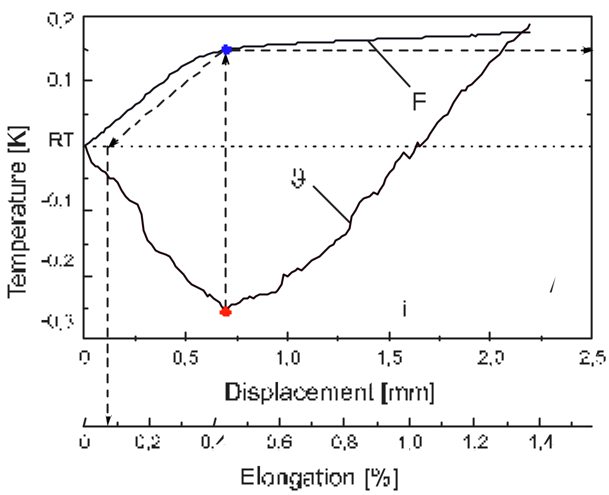

Fig. 2. Temperature vs. elongation obtained for standard tensile test specimen

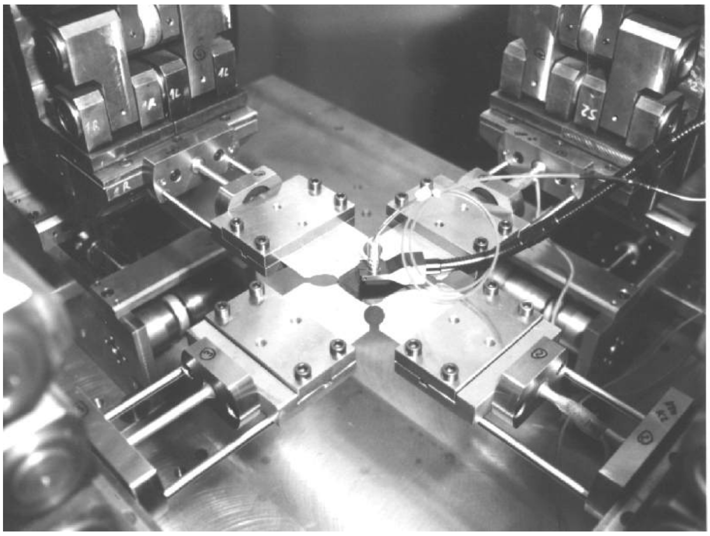

***Fig. 3**. Cruciform specimen and the temperature measurement device*

fraction of a degree due to thermo-elastic cooling. When plastic flow begins, the temperature rises strongly (Figure 2). In contrast with the definition of the yield point given by the standards, the minimum of the temperature vs. elongation enables a definition without any arbitrariness. In general, this method overestimates the value of the yield stresses as compared to the classical one that uses stress gauges. Biaxial tensile deformation was carried out by means of a CNC stretch-drawing facility designed and built at the Institute for Metal Forming Technology, Stuttgart University (Figure 3). The predictions of the yield criteria have been tested for an AA3103, AA5005, AA5182 and AA6181 aluminium alloys. The experimental values needed as input data by the computer program used for the numerical identification of the material parameters involved in the expression of the BBC2000 yield criteria are presented in the Table 1.

4. RESULTS

Table 2 shows the values of the coefficients used in both yield functions obtained by numerical identification. The corresponding values of k and Y are also presented for completeness. The yield surface predicted by the different yield criteria for the AA3103, AA5005, AA5182 and AA6181 aluminium alloys are presented in Figures 4 to 7. The experimental data obtained at Institute of

	AA3103	AA5005	AA5182	AA6181
s_0[Mpa]	55	50	143.5	142
s_{45}[Mpa]	58	52	138.9	138
s_{90}[Mpa]	61	51	142.5	137
s_b[Mpa]	60	54	152	134
r_0	0.639	0.810	0.642	0.672
r_{45}	0.513	1.194	1.039	0.606
r_{90}	0.605	0.426	0.829	0.821

***Table 1**. Mechanical parameters for different aluminium alloys*

	AA3103	AA5005	AA5182	AA6181
a	0.8304	0.7152	0.7400	0.5507
b	1	0.7676	0.0827	1
c	1	0.4454	0.0439	1
M	0.3653	0.6257	5.7266	0.5439
N	0.4643	0.5440	5.1932	0.4983
P	0.5639	1.2258	11.9618	0.4910
Q	-0.4540	-1.1849	-11.695	-0.5336
R	0.9905	4.1748	657.954	0.9872
k	4	4	4	4
Y	55	50	143.5	142

***Table 2**. Coefficients used in BBC2000 criterium for different aluminium alloys*

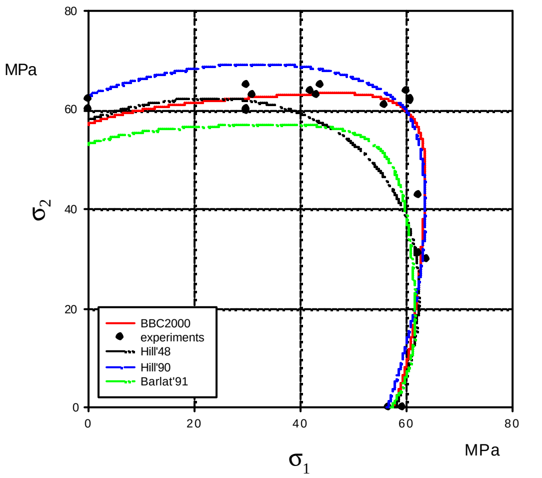

Fig. 4. *Experimental and theoretical yield loci for AA3103-0 aluminum alloy*

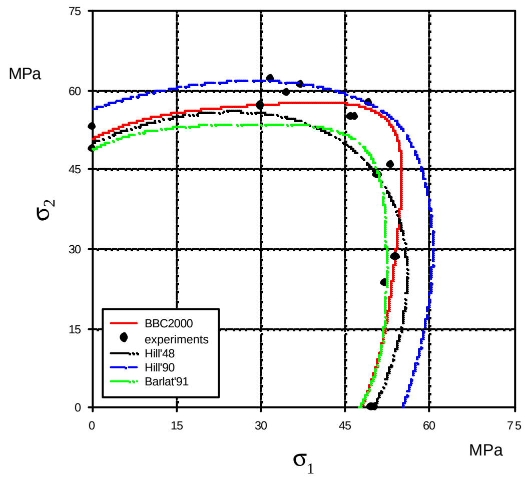

Fig. 5. *Experimental and theoretical yield loci for AA5005-0 aluminum alloy*

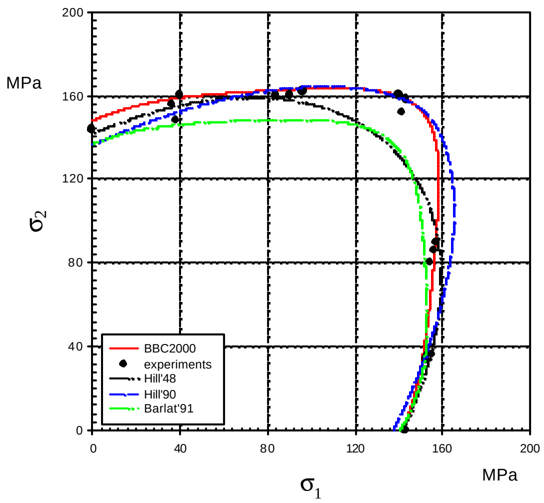

Fig. 6. *Experimental and theoretical yield loci for AA5182 aluminum alloy*

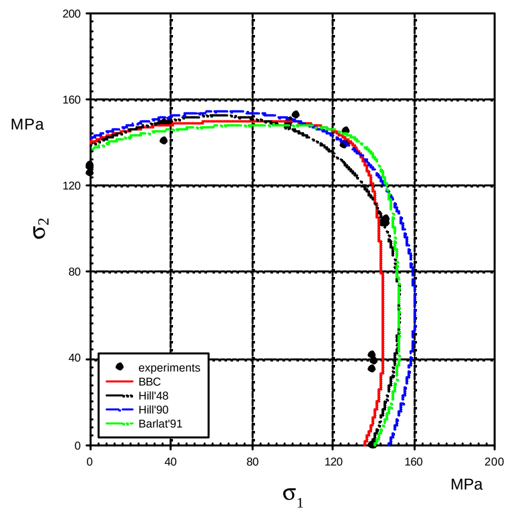

Fig. 7. *Experimental and theoretical yield loci for AA6181 aluminum alloy*

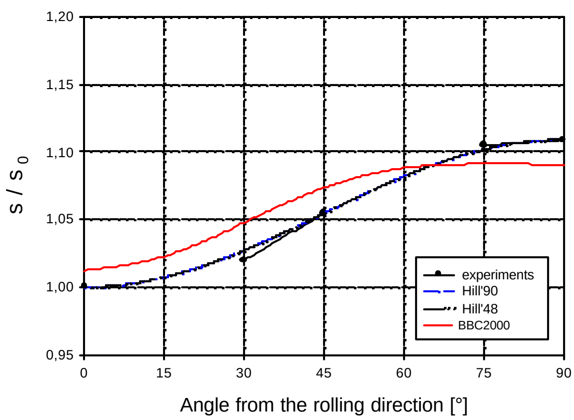

Fig. 8. *Distribution of the uniaxial yield stress for AA3103 aluminum alloy*

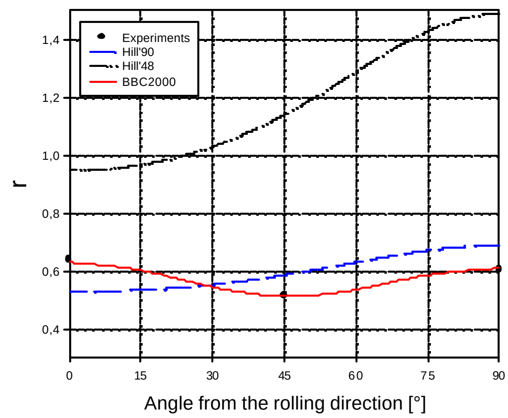

Fig. 9. *Distribution of the anisotropy coefficient for AA3103 aluminum alloy*

Metal Forming Technology are also plotted on the diagrams. A very good agreement has been found between predicted and experimental yield loci for BBC2000 yield criterion. The predicted distribution of the uniaxial yield stress and the anisotropy coefficient with respect to the angle with the rolling direction are shown in the Figures 8 and 9 for only one alloy, namely AA3103-0. Similar distributions have been found for AA5005, AA5182 and AA6181 aluminium alloys. A very good agreement has been found between predicted and experimental distributions of the anisotropy coefficient using BBC2000 yield criterion. A better prediction of the uniaxial yield stress has been found by using Hill's family yield criterion (deviations between theory and experiments are bellow 3% by using BBC2000).

5. CONCLUSIONS

The anisotropic plastic behaviour of AA3103, AA5005, AA5182 and AA6181 aluminium alloys has been modelled using the phenomenological description proposed by Hill'48, Hill'90, Barlat'91 and BBC2000 yield criteria. Biaxial tensile deformation tests were carried out on cruciform specimens using a CNC stretch-drawing facility. The beginning of plastic yield was monitored by temperature measurements. Comparison with data show that the BBC2000 yield criterion can successfully describe anisotropic behaviour of all tested aluminium alloys.

REFERENCES

1. Hill R., A theory of the yielding and plastic flow of anisotropic metals, Proc.Roy.Soc. London, (1948),281-297.
2. Hill R., Theoretical plasticity of textured aggregates, Math. Proc. Cambridge Phil. Soc., 85 (1979), 179-191.
3. Hill R, Constitutive modeling of orthotropic plasticity in sheet metals, J. Mech. Phys. Solids, 38 (1990), 405-417.
4. Hill R., A User-friendly theory of orthotropic plasticity in sheet metals, Int. J. Mech. Sci. 15 (1993), 19-25.
5. Hosford W.F., A generalized isotropic yield criterion, J. Appl. Mech. 39 (1972), 607-609.
6. Hosford W.F., On yield loci of anisotropic cubic metals, Proc. 7th North American Metalworking Conf., SME, Dearborn, MI (1979),191-197.
7. Barlat F., Richmond O., Prediction of tricomponent plane stress yield surfaces and associated flow and failure behaviour of strongly textured FCC polycrystalline sheets, Mat. Sci. Eng.,95(1987), 15.
8. Barlat F., Lian J., Plastic behaviour and stretchability of sheet metals (Part I) A yield function for orthotropic sheet under plane stress conditions, Int. J. of Plasticity 5 (1989), 51-56.
9. Barlat F., Lege D.J., Brem J.C., A six-component yield function for anisotropic materials, Int. J. of Plasticity, 7(1991), 693-712.
10. Barlat F.et al Yielding description for solution strengthened aluminium alloys, Int.J.of Plasticity, 13(1997),385-401.
11. Barlat F.et al, Yield function development for aluminium alloy sheets, J. Mech. Phys. Solids, 45(1997), 1727-1763.
12. Karafillis A.P., Boyce M.C., A general anisotropic yield criterion using bounds and a transformation weighting tensor, J. Mech. Phys. Solids, 41 (1993), 1859-1886.
13. Barlat F. et al, Plane stress yield function for aluminium alloy sheets, International Journal of Solids and Structures, in press, 2000.
14. Banabic D., Comsa D.S., Balan T., A new yield criterion for orthotropic sheet metals under plane-stress condition, Proc. of the Conf. TPR200 (Ed. Banabic D.), Cluj-Napoca, May 2000, 217-224.
15. Banabic, D., Comsa D.S., Balan T., Yield criterion for orthotropic sheet metals, Proc. of the Conf. Metal Forming 2000, Krakow, Balkema, 713-716.
16. Cazacu O., Barlat F., Generalization of Drucker's yield criterion to orthotropy, Mathematics and Mechanics of Solids, in press, 2001.
17. Vegter,H., Drent, P., Huetnik, J., A planar isotropic yield criterion based on mechanical testing at multi-axial stress states, Proc. Numiform, 1995, 345-350.
18. Pöhlandt K., Banabic D., Lange K., Equi-biaxial anisotropy coefficient used to describe the plastic behavior of sheet metal, Proc. 5th ESAFORM Conference, Krakow, 2002.
19. Banabic, D. et al, Formability of Metallic Materials, Springer, Berlin-Heidelberg, 2000.
20. Kreißig R., Theoretische und experimentelle Untersuchungen zur plastischen Anisotropie, Diss. TU Karl-Marx-Stadt, 1981.
21. Müller W., Beitrag zur Charakterisierung von Blechwerkstoffen unter zweiachsiger Beanspruchung, Diss. Universität Stuttgart, Springer-Verlag, 1996.
22. Sallat G., Theoretische und experimentelle Untersuchungen zum Fließverhalten von Blechen im zweiachsigen Hauptspannungszustand, Diss., TU Karl Marx Stadt, 1988.