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DD3MAT - a code for yield criteria anisotropy parameters identification.

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DD3MAT – a code for yield criteria anisotropy parameters identification.

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Abstract. This work presents the main strategies and algorithms adopted in the DD3MAT in-house code, specifically developed for identifying the anisotropy parameters. The algorithm adopted is based on the minimization of an error function, using a downhill simplex method. The set of experimental values can consider yield stresses and r-values obtained from in-plane tension, for different angles with the rolling direction (RD), yield stress and r-value obtained for biaxial stress state, and yield stresses from shear tests performed also for different angles to RD. All these values can be defined for a specific value of plastic work. Moreover, it can also include the yield stresses obtained from in-plane compression tests. The anisotropy parameters are identified for an AA2090-T3 aluminium alloy, highlighting the importance of the user intervention to improve the numerical fit.

1. Introduction

Sheet metal forming processes are nowadays designed and optimized virtually using finite element analysis (FEA), which is consensually accepted as the main reason for the huge decrease in time-to-market life cycle and for notable savings in terms of money, time and effort in the design, production and process set-up of new formed parts. However, the success of finite elements solvers on the design and optimization of sheet metal formed parts is strongly dependent on their ability to accurately describe the material's mechanical behaviour. Sheet metals generally exhibit anisotropic mechanical behaviour due to the rolling process, characterized by the symmetry of the mechanical properties with respect to three orthogonal planes, i.e. orthotropic behaviour. Thus, different mechanical behaviours are expected for different loading directions and conditions. Phenomenological models are the most widely used approach to describe the elastoplastic response of metallic sheets, since they are computationally efficient when compared with microscopic models. The material's orthotropic behaviour is modelled by the yield surface, used to describe the yielding and the plastic flow of the material, based on the hardening law selected. This dual role of the yield surface requires a particular care and accuracy in its modelling and numerical implementation. The material anisotropy parameters identification must be performed in a way that a given yield criterion should reproduce the materials mechanical behaviour as close as possible. Moreover, since sheet metal forming processes are carried out with inhomogeneous deformation and under multiaxial strain paths it is important to use as much information as possible.

In this work DD3MAT in-house code is used to identify the anisotropy parameters for an AA2090-T3 aluminium alloy [1], considering three yield criteria YLD91 [2], CB2001 [3] and CPB06 [4]. The predicted in-plane distribution of the yield stresses and r-values evolution, as well as the yield surfaces, are discussed to show that a more or less accurate fit of the experimental data is achieved, depending on the selected yield criterion and on the user intervention, through the selection of the weighting factor for each test result.

2. DD3MAT – yield criteria parameters identification code.

The anisotropy parameters should be determined such that the yield criterion reproduces the material's mechanical behavior as close as possible. The most used experimental results for the identification of anisotropy parameters are the yield stresses and r-values obtained from in-plane tension, for different angles (θ) with the RD. In order to improve the description of the yield surface, it is also recommended to experimentally determine the biaxial yield stress and the biaxial anisotropy coefficient [5–7]. For the CPB06 yield criterion, uniaxial compression experimental results are also necessary for describing the strength differential effects. However, when performing compression tests for thin metallic sheets it is necessary to avoid buckling effects. This requires the use of small specimens, leading to supplementary difficulties in the acquisition and analysis of experimental results, particularly for high strain values [8]. The anisotropy parameters for the three selected yield criteria were obtained with the DD3MAT in-house code. The procedure adopted is based in an optimization problem regarding the minimization of an error function, evaluating the difference between the estimated values and the experimental ones, as follow

$$\begin{aligned}F(\mathbf{A}) = \sum_{\theta=0}^{90}\Big[& w_{\sigma_\theta^{\mathrm{T}}}\left(\sigma_\theta^{\mathrm{T}}(\mathbf{A})/\sigma_\theta^{\mathrm{T}}-1\right)^2 + w_{\sigma_\theta^{\mathrm{C}}}\left(\sigma_\theta^{\mathrm{C}}(\mathbf{A})/\sigma_\theta^{\mathrm{C}}-1\right)^2 + w_{r_\theta}\left(r_\theta(\mathbf{A})/r_\theta-1\right)^2\Big] \\ & + w_{\sigma_b}\left(\sigma_b(\mathbf{A})/\sigma_b-1\right)^2 + w_{r_b}\left(r_b(\mathbf{A})/r_b-1\right)^2\end{aligned} \quad (1)$$

where $\mathbf{A}$ represents the set of parameters associated with the selected yield criterion. $\sigma_\theta^{\mathrm{T}}$, $\sigma_\theta^{\mathrm{C}}$ and r_θ are the experimental yield stresses in tension, compression and r-values determined in uniaxial tension, respectively, obtained from the uniaxial tests for a specific orientation (θ) with respect to RD. σ_b is the experimental yield stress obtained from the equibiaxial tensile test, r_b is the experimental r-value obtained from the disc compression test, and $\sigma_\theta^{\mathrm{T}}(\mathbf{A})$, $\sigma_\theta^{\mathrm{C}}(\mathbf{A})$ $r_\theta(\mathbf{A})$, $\sigma_b(\mathbf{A})$ and $r_b(\mathbf{A})$ are the correspondent values predicted from the adopted yield criterion. Such procedure can be considered a generalization of the one proposed by Banabic et al., 2005 [9]. The weighting factors, $w_{\sigma_\theta^{\mathrm{T}}}$, $w_{\sigma_\theta^{\mathrm{C}}}$, w_{r_θ}, w_{σ_b} and w_{r_b} are used to balance the influence of the experimental data. Nevertheless, the selection of the weighting factors is normally a manual procedure, strongly dependent on users' expertise and knowledge. The identification procedure, defined in (1) also implies the pre-selection of an initial yield stress or the hardening law parameters, if a specific value of plastic work is defined to select the experimental values for the yield stresses.

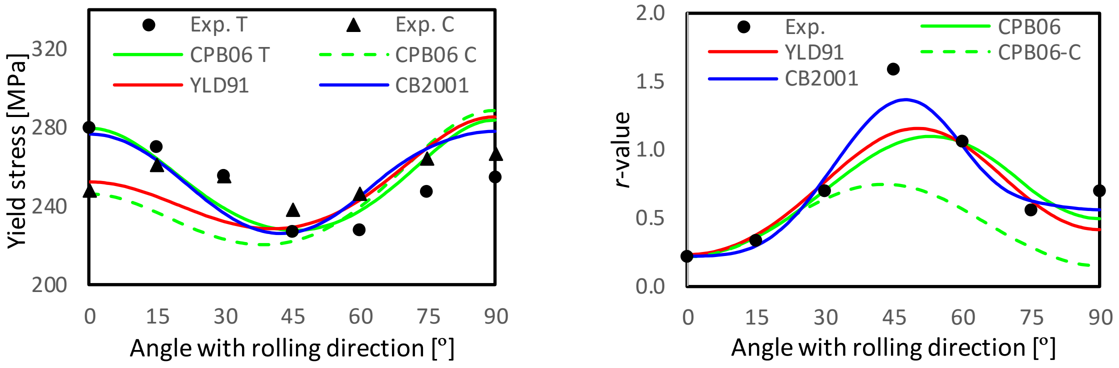
3. Results and discussion

The anisotropy parameters for the three previously mentioned yield criteria were identified for an AA2090-T3 aluminium alloy, for which the experimental values of $\sigma_\theta^{\mathrm{T}}$, $\sigma_\theta^{\mathrm{C}}$, r_θ (at each 15° with RD), σ_b and r_b are available [1].

Figure 1 shows the evolution of the yield stress and r-values with the angle from RD, for the three yield criteria, obtained considering all weighting factors equal to 1.0 (labelled "Set 1"). As expected, YLD91 shows a less accurate fit when compared with the other yield criteria, mainly for the yield stresses. CPB06 presents a better fit for the yield stresses, when compared with the YLD91, with the added benefit of also describing the materials' behavior for compression stress states. Regarding the CB2001, both yield stresses and r-values are globally well described. Nevertheless, it is possible to see that all yield criteria fail to capture the r-value at 45° and tend to overestimate the yield stresses for angles closer to the transverse direction (TD). Therefore, a new set of parameters was identified, through the selection of the weighting factors (shown in Table 1), i.e. with user intervention, labelled "Set 2".

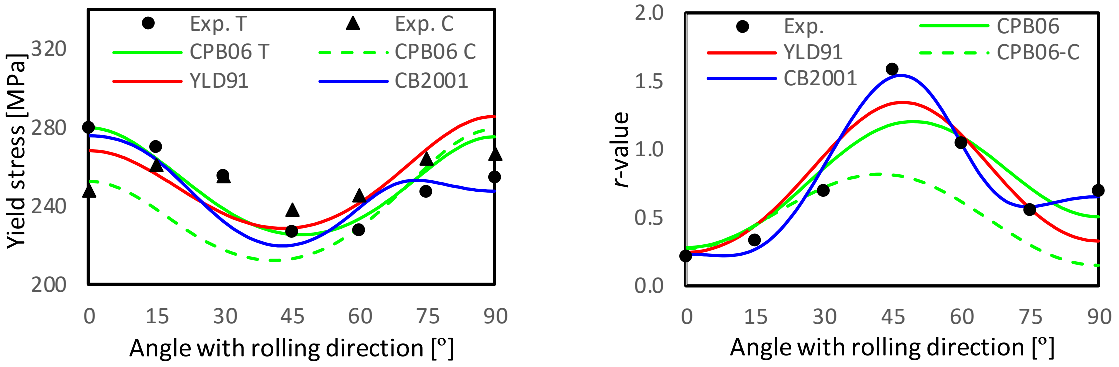
Figure 2 shows the evolution of the yield stress and r-values with the angle from the RD, for the three yield criteria, considering the user intervention. For the CB2001, the description is enhanced mainly for yield stresses for angles closer to TD and the predicted r-values at 45° and 90° are closer to the experimental ones. For the YLD91, the main improvement occurs for yield stresses closer to the rolling direction and the r-value at 45°. The CPB06 also benefited from the user's input in the identification procedure since the yield stresses evolution in tension and compression are globally closer to the experimental values.

Figure 3 presents the yield surfaces for the three considered yield criteria in the $\sigma_1 - \sigma_2$ plane considering, or not, user intervention. These results, together with Table 2, allows analyzing the material behavior for stress states other than uniaxial tensile stress. YLD91 presents lower experimental σ_b values, for both sets, slightly more accurate for Set 2. The CB2001 yield criterion predicts accurate σ_b and r_b values for both stets, but Set 1 presents a r_b value lower than the experimental, while it is slightly higher for Set 2. Globally, CPB06 presents the σ_b and r_b values least accurate, since the introduction of the compression yield stress in the optimization procedure reduces the relative importance of these values in the objective function. A summary of the parameters identified for the three yield criteria, considering both sets, is presented in Table 3, highlighting the parameters' interdependence.



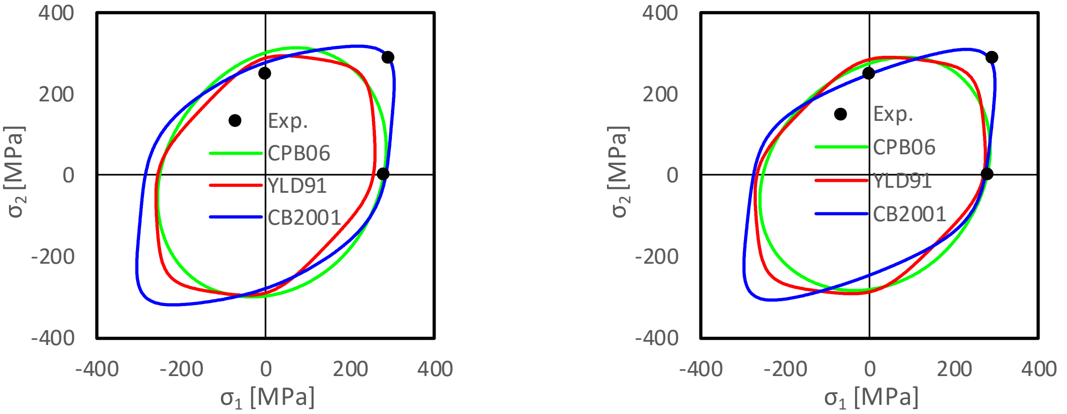
(a) (b)

Figure 1. Experimental and predicted (a) yield stresses and (b) r-values (Set 1).



(a) (b)

Figure 2. Experimental and predicted (a) yield stresses and (b) r-values (Set 2).



(a) (b)

Figure 3. Predicted yield surfaces in the $\sigma_1 - \sigma_2$ plane (a) Set 1 and (b) Set 2.

Table 1. Experimental and predicted yield stress and r -values for the biaxial test.

CB2001	$w_{r_{45}}=5$ $w_{r_{75}}=5$ $w_{r_{90}}=5$ $w_{\sigma_b}=20$ $w_{\sigma_{60}^{\mathrm{T}}}=10$ $w_{\sigma_{75}^{\mathrm{T}}}=10$ $w_{\sigma_{90}^{\mathrm{T}}}=10$
YLD91	$w_{r_{45}}=5$ $w_{\sigma_b}=20$ $w_{\sigma_{0}^{\mathrm{T}}}=20$ $w_{\sigma_{15}^{\mathrm{T}}}=20$ $w_{\sigma_{75}^{\mathrm{T}}}=20$ $w_{\sigma_{90}^{\mathrm{T}}}=20$
CPB06	$w_{r_{45}}=7$ $w_{\sigma_b}=20$ $w_{\sigma_{90}^{\mathrm{T}}}=30$ $w_{\sigma_{15}^{\mathrm{C}}}=40$ $w_{\sigma_{30}^{\mathrm{C}}}=5$ $w_{\sigma_{45}^{\mathrm{C}}}=5$ $w_{\sigma_{60}^{\mathrm{C}}}=5$ $w_{\sigma_{75}^{\mathrm{C}}}=5$ $w_{\sigma_{90}^{\mathrm{C}}}=40$

Table 2. Experimental and predicted yield stress and r -values for the biaxial test.

		Set 1			Set 2		
	Exp.	CB2001	YLD91	CPB06	CB2001	YLD91	CPB06
σ_b	289.4	289.6 (0.06%)	235.1 (-18.7%)	232.8 (-19.6%)	285.9 (-1.2%)	239.4 (-17.3%)	229.5 (-20.7%)
r_b	0.67	0.66 (-0.74%)	0.57 (-15.7%)	0.78 (+15.8%)	0.66 (-1.5%)	0.76 (+12.7%)	0.89 (+33.3%)

Table 3. Anisotropy parameters identified for the considered yield criteria.

	Set	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4	b_5	b_{10}	c
CB2001	1	0.728	1.402	1.334	1.525	3.576	-0.838	-1.983	-0.581	-4.580	-0.567	0.608
	2	1.358	1.848	1.075	1.709	5.357	-0.623	-4.386	-3.654	-6.046	-0.882	0.857

	Set	c_1	c_2	c_3	c_6	m
YLD91	1	1.069	1.300	0.856	1.213	8
	2	1.110	1.224	0.835	1.238	8

	Set	C_{11}	C_{22}	C_{33}	C_{66}	C_{23}	C_{13}	C_{12}	k
CPB06	1	-1.010	0.475	1.199	-1.082	-0.102	0.104	-0.012	-0.057
	2	-0.818	0.449	1.232	-1.224	-0.088	-0.060	-0.819	-0.050

Note that, for metal sheets, the off plane parameters cannot be experimentally evaluated. Thus, parameters a_5, a_6 and b_k $(k=6,7,8,9,11)$, for the CB2001, c_4, c_5 for the YLD91 and C_{44}, C_{55} for the CPB06 take the corresponding isotropic values, i.e. 1.0.

4. Conclusions

The results presented show the ability of DD3MAT in-house to perform the identification of the anisotropy parameters for different yield criteria. The classical identification procedure adopted allows the user to control the importance of each test through the weighting factors. However, the users' input and knowledge is only as good as the flexibility allowed by the yield criterion considered.

Acknowledgments

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