

## Study on the Effect of Anisotropy on Plastic Flow Localization of Third Generation Advanced High Strength Steel

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**Keywords:** Third generation of advanced high strength steel, Formability, Anisotropy, Constitutive equations, MK model, Numerical simulation

**Abstract.** The aim of this work is to analyze the effect of the anisotropy on the formability of the third generation of advanced high strength steel (3genAHSS) from experimental and theoretical point of view. The reference material is the USS CR980XG3™ AHSS, a 3genAHSS 980T/600Y- retained austenite bearing-high elongation steel grade. A careful experimental work on the selected 3genAHSS characterization has been performed. The anisotropy factors and the yield stresses have been identified from tensile tests at several orientations with respect to the rolling direction. The experimental forming limit diagram under linear strain paths has been determined using Nakajima tests and the Ericksen test for the biaxial stretching, respectively. The Marciniak-Kuczynski analysis is used to simulate the onset of localized necking through an advanced sheet metal forming limit model. Yld2000-2d yield condition gives the initial shape of the yield locus. Swift strain-hardening power law is used to describe the strain hardening of the material. The effect of the anisotropy on the forming limits of 3genAHSS steel is analyzed. A proper reproducibility of the experimental tendencies of anisotropic factor distribution and the yield stress as a function of the tensile loading axis by the selected constitutive equations is achieved. A good accuracy of the FLD model on the prediction of the experimental results is found.

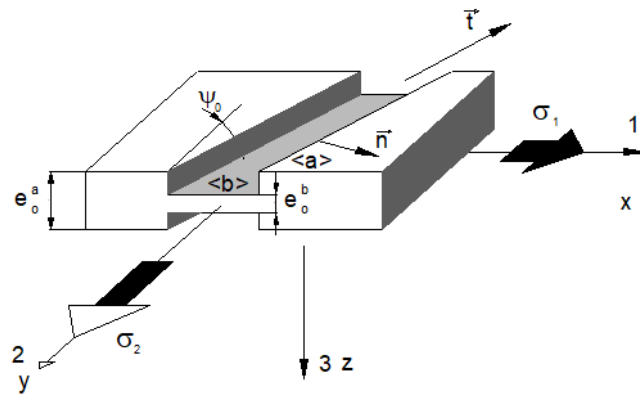
### Introduction

The 3genAHSS are the most innovative steels with excellent strength-ductility combinations, significantly improved compared to the first generation AHSS, at a lower cost than the second generation AHSS. One of the main challenges of the steel and automotive industry is the failure in AHSS steels, and concerning the 3genAHSS, there is a lack of research in this field. To predict the formability of sheet metals, the Forming Limit Diagram (FLD) introduced by Gensamer [1] in 1946, according to the recent study of Banabic et al. [2], is the method applied the most in the industry. Several physical factors influence the forming limits of sheet metals: strain hardening, plastic anisotropy, strain rate sensitivity and strain path. The theoretical analysis of plastic instability and flow localization will contribute to the prevention of the sheet metal forming process failures, to the analysis of each parameter's influence on the necking occurrence and to the press performance improvement. To date, the Marciniak-Kuczynski (MK) [3] model has become the most important tool

in constructing the FLDs for various structural materials and deformation processes. The aim of this work is to analyze the formability of the third generation advanced high strength steel with emphasis on the effect of its plastic anisotropy on it. Therefore, the following topics were taken into account in the present study: (i) experimental mechanical characterization and determination of the forming limits of a 3genAHSS steel sheet; (ii) numerical prediction of the FLDs using a MK model-based software; (ii) study of the effect of the plastic anisotropy of 3genAHSS steel on the forming limits. The selected constitutive equations applied in the MK model are the Yld2000-2d yield function [4] and the Swift hardening law. The parameters of the material models were identified on the base of the experimental data. For validation of the model, the experimental and predicted forming limits are compared.

### Theoretical Computation of the Onset Of Plastic Flow Localization

In this work, the code for predicting the forming limits developed by Butuc et al. [5] was used for the calculation of the theoretical Forming Limit Diagrams. The numerical simulation of the plastic flow localization is carried out in the heterogeneous materials framework using the Marciniak-Kuczynski (MK) analysis, schematically illustrated in Fig. 1, and the Theory of Plasticity.



**Figure 1.** MK analysis: Initial geometrical imperfection

The model is based on the growth by plastic deformation within a thin sheet of an initial defect ( $f_0$ ) in the form of a groove-like, narrow band of diminished thickness. The  $x$ ,  $y$ ,  $z$ -axes correspond to rolling, transverse and normal directions of the sheet, whereas 1 and 2 represent the principal stress and strain directions in the homogeneous region.  $n$ ,  $t$ ,  $z$  are the set of axes bound to the groove in which  $t$  denotes the longitudinal axis. For the computation of the left side of the diagram, in accordance with the Marciniak model [6], it is considered a variation between  $0^\circ$  and  $90^\circ$  from rolling direction (RD) of the initial inclination angle of the band,  $\psi_0$ , with respect to the minor principal axis of the stress tensor. The computations of homogeneous and heterogeneous zones are considered independent and connected through the MK conditions: force equilibrium and geometrical compatibility, in accord with the method proposed by Butuc et al. [7]. The stress and strain states are computed by using the theory of plasticity. The principal strains in the homogeneous zone when the necking criterion is reached, define the forming strain limits. The limit point on the FLD for each considered strain path is obtained through the minimization of the principal strain in the homogeneous zone, versus  $\psi_0$ . The material is assumed to have a rigid-plastic behaviour with initial yield locus shape described by the Yld2000-2d plane stress yield criterion.

The plastic anisotropy is introduced in the Yld2000-2d plane stress yield function of Barlat et al. [4] by two linear transformations on the Cauchy stress tensor. The Yld2000-2d plane stress yield function, in terms of the deviatoric stress components, is expressed as:

$$\phi = \phi'(\tilde{\mathbf{S}}') + \phi''(\tilde{\mathbf{S}}'') = 2\bar{\sigma}_Y^a \quad (1)$$

where  $\bar{\sigma}_Y$  is the effective stress,  $a$  is an exponent connected to the crystal structure,  $\phi'$  and  $\phi''$  are two isotropic functions defined by

$$\phi'(\tilde{S}') = |\tilde{S}'_1 - \tilde{S}'_2|^a \quad (2)$$

$$\phi''(\tilde{S}'') = |2\tilde{S}''_2 + \tilde{S}''_1|^a + |2\tilde{S}''_1 + \tilde{S}''_2|^a \quad (3)$$

$\tilde{S}'$  and  $\tilde{S}''$  are the linear transformations of the effective stress tensor  $s$  defined as the deviatoric part of the Cauchy stress:

$$\tilde{S}' = C' s, \quad \tilde{S}'' = C'' s \quad (4)$$

where  $C'$  and  $C''$  contain the material anisotropy coefficients.

The hardening behavior of the material is approximated by the Swift hardening law.

$$\bar{\sigma} = K(\varepsilon_0 + \bar{\varepsilon})^n \quad (5)$$

where  $\bar{\sigma}$  is the flow stress,  $\bar{\varepsilon}$  the effective plastic strain, while  $K$ ,  $\varepsilon_0$  and  $n$  are material parameters.

## Results and Discussion

The selected material is the USS CR980XG3™ AHSS, a 3genAHSS 980T/600Y- retained austenite bearing-high elongation steel grade. The corresponding values for the initial yield stresses and anisotropy factor  $r$  for three uniaxial tensile directions, the balanced biaxial yield stress  $\sigma_b$  and the biaxial anisotropy coefficient  $r_b$  are listed in table 1. The anisotropy parameters for the Yld2000-2d yield function are calculated, and presented in table 2, for different exponents, using a numerical identification from the experimental data:  $r_0$ ,  $r_{45}$ ,  $r_{90}$ ,  $r_b$ ,  $\sigma_0$ ,  $\sigma_{45}$ ,  $\sigma_{90}$ ,  $\sigma_b$ . The two values of the exponent “a” of the Yld2000-2d yield function are used in the identification of the coefficients of the yield function, to analyze the effect of the sharpness of the yield locus in equibiaxial stretching in the predicted forming limits.

**Table 1.** The uniaxial tensile properties of USS CR980XG3™ AHSS

Orientation	Yield stress [MPa]	Biaxial yield stress $\sigma_b$ [MPa]	Anisotropy factor $r$	Biaxial anisotropy factor $r_b$
0°	602		0.861	
45°	642	603.7	0.957	0.971
90°	667		0.895	

**Table 2.** Anisotropy coefficients of the Yld2000-2d yield function

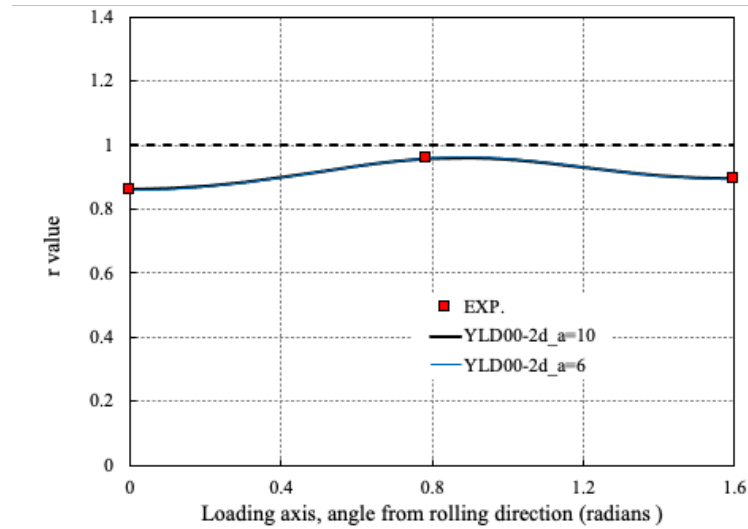
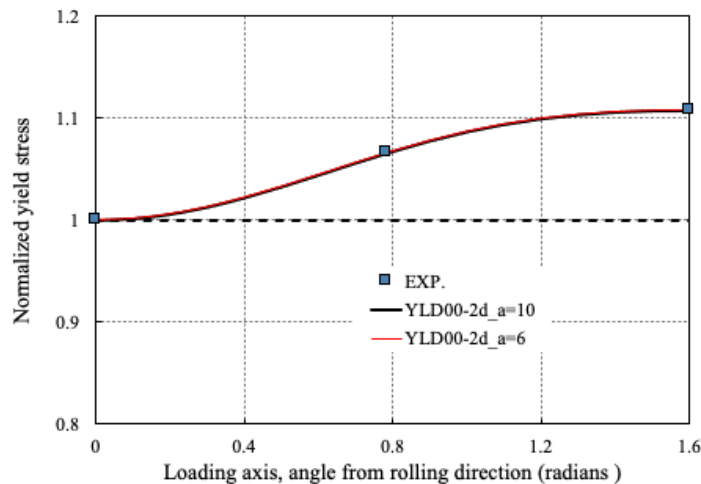
Material	a	$\alpha_1$	$\alpha_2$	$\alpha_3$	$\alpha_4$	$\alpha_5$	$\alpha_6$	$\alpha_7$	$\alpha_8$
CR980XG3™	6	1.106	0.79	1.125	0.963	0.986	0.951	0.944	0.862
	10	1.105	0.794	1.107	0.957	0.992	0.974	0.941	0.87

The material parameters of the Swift hardening law are presented in table 3.

**Table 3.** Material parameters of the Swift hardening law

$K$ [MPa]	$\varepsilon_0$	$n$
1880	0.0069	0.231

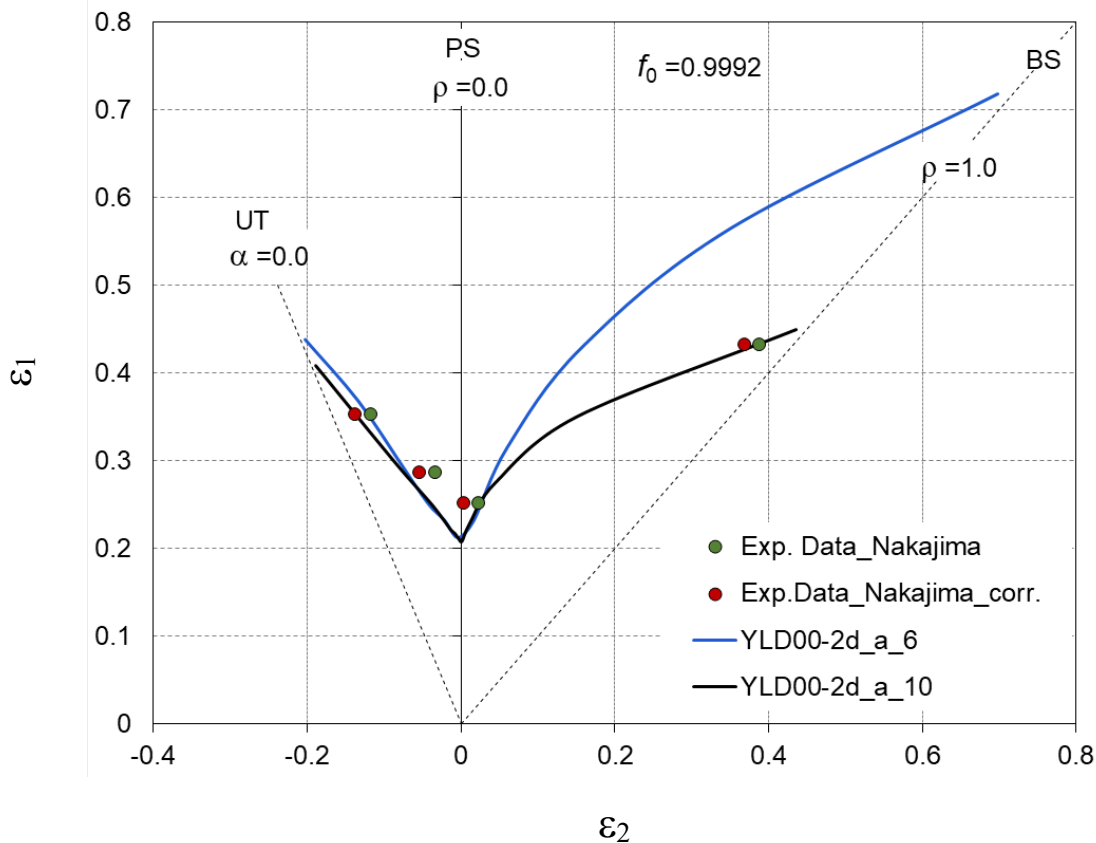
The material plastic anisotropy is mainly pointed out through the anisotropy coefficients values and the yield stresses. Figs. 2 and 3 show, the evolution of the anisotropy factor and of the yield stress, respectively, as a function of the tensile loading axis between 0° and 90° degrees. In all graphics, the acronym YLD00-2d is used for the Yld2000-2d simulated results.

**Figure 2.** Distribution of anisotropy coefficients**Figure 3.** Normalized yield stress as a function of the loading axis

The material presents a normal anisotropy close to 1 and a weak planar anisotropy close to -0.1. A particular property of the studied 3genAHSS steel is the r-values less than 1, an unusual fact for a traditional steel sheet. The balanced biaxial yield stress is almost identical with the uniaxial yield stress in RD, corroborating the observation of Woodthorpe and Pearce[8] for materials exhibiting r values less than 1. The highest yield stress is observed in the transverse direction. The Yld2000-2d predicted results reproduce accurately the experimental tendencies of the anisotropy factors and the yield stress.

The experimental forming limit diagram under linear strain paths has been determined using the Nakajima tests and the Erichsen test for the biaxial stretching, respectively. An electro-chemical method was used to print on the surface of the test pieces a grid of circles. The strains were calculated from measurements of deformed grids using a NC Profile Projector. The onset of localized necking was determined from strain distribution profiles near the necking region. The slight right shift of the experimental curve is due to the initial nonlinearity of the Nakajima experiments. Hence, a small correction (0.02) on the experimental forming limits (Exp\_Data\_Nakajima) was applied to shift the curve to the left (Exp\_Data\_Nakajima\_corr).

Fig. 4 shows the experimental forming limits for the USS CR980XG3™ AHSS steel under proportional loading, and the ones simulated with the selected constitutive equations namely, the Yld2000-2d yield function and the Swift hardening law. To achieve the best agreement with the experimental data, the initial value of the MK geometrical defect was set to 0.9992, a typical value of the MK inhomogeneity as suggested by Marciniak et al. [9]. The strain paths are defined by the stress ratio  $\alpha$ , expressed as  $\sigma_2/\sigma_1$  and by the strain ratio  $\rho$  expressed as  $d\varepsilon_2/d\varepsilon_1$ , respectively. The acronyms UT, PS and BS are used for uniaxial tension, plane strain and biaxial stretching, respectively.



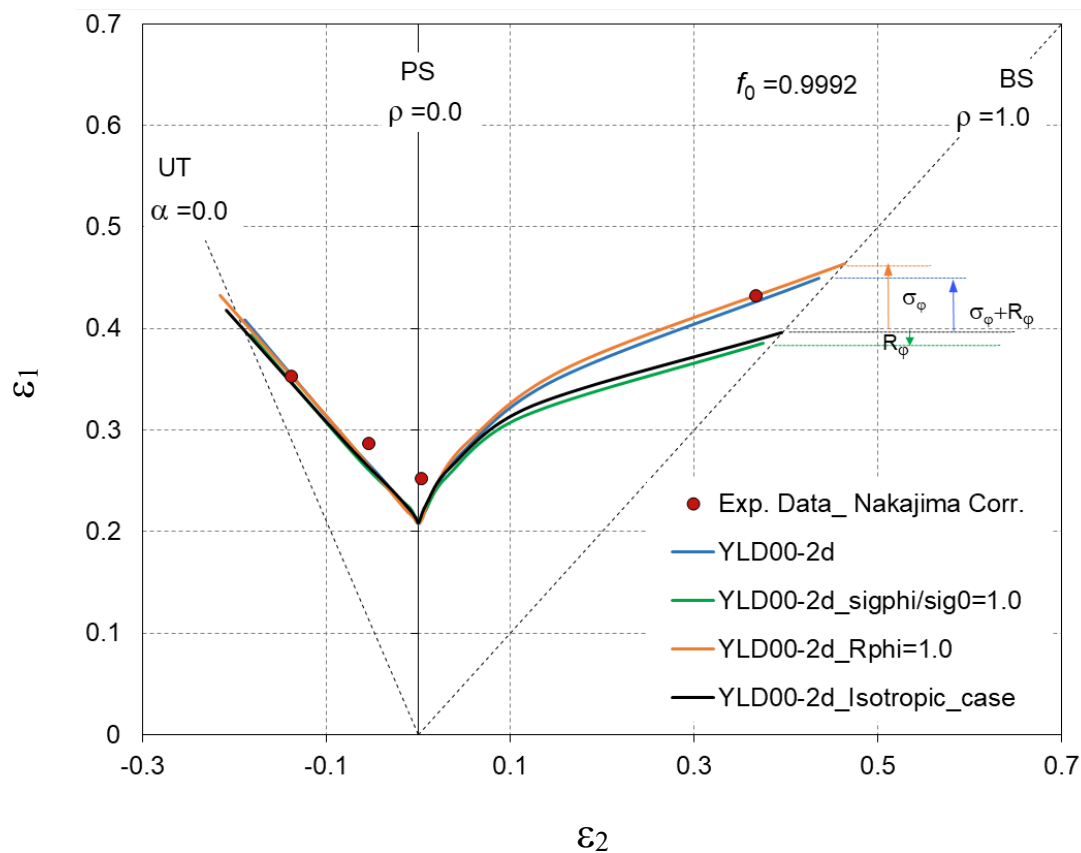
**Figure 4.** Experimental and theoretical FLDs for USS CR980XG3™ AHSS

The exponent “a” of the yield function controls the sharpness of the yield locus in equibiaxial stretching, which is very important in FLD predictions. The increase of the parameter “a” enables the increase of the sharpness of the yield locus in equibiaxial stretching and subsequently the decrease of the predicted forming limits. It is well known that an exponent of  $a=6$  for materials with Body-Centered Cubic (BCC) crystal structure and an exponent of  $a=8$  for materials with Face-Centered Cubic crystal structure (FCC) are recommended.

In Fig. 4 it is observed the over estimation of the predicted forming limits in the biaxial stretching, with an “a” of 6, which is usually used for steels. Therefore, to increase the sharpness of the yield surface and consequently to decrease the limit strains, a value of  $a=10$  was selected for the simulation. In this way, the accuracy of the predicted FLD was significantly improved. Hence, for FLD

prediction, it was found that the exponent of the Yld2000-2d yield function “a” of 10 was more adequate for USS CR980XG3™ AHSS steel. In a recent study [10] it was found an “a” of 5 for TWIP steel and it was suggested that more values beside of 6 and 8 should be explored specially in the case of new structural materials. The complex multi-phase microstructure of 3genAHSS steel, a mixture of ferrite, martensite and austenite, can be tentatively assumed as the reason of the selected value of the exponent “a”. However, this value of “a” needs further validation through the experimental yield locus. Anyway, it was proved, once again, that to predict the FLDs, it is extremely important for the yield function to reproduce accurately the sharpness of the yield surface in the biaxial stretching region. Besides, it is observed a good correlation between theoretical and experimental forming limits for both of cases in the left part of the FLD. The forming limits in the plane strain is slightly underestimated.

The effect of the anisotropy of the 3genAHSS steel on the predicted forming limits was analyzed by assuming 4 conditions in which it is considered: i) the anisotropy of the material through the experimental values of  $r$  and the yield stresses; ii) the anisotropy of the  $r$  factors, through their experimental values and the normalized yield stresses of 1; ii) the anisotropy of the yield stresses, through the experimental values of the normalized yield stresses and the  $r$ -values of 1; and iv) the isotropic case, with the  $r$ -values of 1 and the normalized yield stresses of 1. The coefficients of Yld2000-2d, with “a” of 10, were identified for each case and the predicted FLDs are presented in Fig. 5. A general notation was adopted, namely the normalized yield stresses and the anisotropy coefficients at different orientation from RD are expressed by  $\sigma_\phi/\sigma_0$  and  $R_\phi$ , respectively, and by  $\text{sigphi}/\text{sig0}$  and  $R\text{phi}$  in the label graphic of Fig 5.



**Figure 5.** The effect of the anisotropy of USS CR980XG3™ AHSS on FLD

By comparing with the isotropic case, the anisotropy factors of CR980XG3™ steel lead to a very small decrease of the predicted forming limits in the right-hand side of the diagram. This result is explained by their values less than one since the predicted forming limits decrease with the decrease of the anisotropy factors. The effect of the anisotropy of the yield stresses of CR980XG3™ steel leads

to an increase of the predicted forming limits in the right-hand side of the diagram, by comparing with the isotropic case. This result is due to the values of the normalized yield stress higher than one since the forming limits increase with the increase of the normalized yield stress value. In the case of the CR980XG3™ steel, such increase is mainly due to the increase of the yield stress at 90° from RD, since all the other values  $\sigma_\phi/\sigma_0$  are almost one. In the case where the material anisotropy is assumed, the accumulated effect of the anisotropy factors and the yield stress anisotropy is reflected in the predicted forming limits. The pronounced effect of the yield stress anisotropy is noticed due to the increased values of the forming limits in comparison with the ones obtained in the isotropic case. In the left side of the FLD an insignificant effect of the material anisotropy is observed.

## Summary

The plastic properties and the formability of USS CR980XG3™ AHSS have been analyzed. The MK model combined with Yld2000-2d yield function and Swift hardening law is able to predict properly the forming limits of the selected 3genAHSS steel. The Yld2000-2d yield function describes accurately the mechanical behavior of USS CR980XG3™ AHSS and it has an important role in the accurate prediction of its forming limits. It was found that the exponent of the Yld2000-2d yield function “a” of 10 is more suitable for USS CR980XG3™ AHSS FLD prediction. The selected 3genAHSS steel shows a weak anisotropic behavior. Since the anisotropy factors are close to one, only the anisotropy on the yield stress has a well-defined effect on the predicted forming limits, contributing to an increase of their values.

## Acknowledgments

The authors acknowledge support from the Operational Program for Competitiveness and Internationalization, in its FEDER/FNR component and the Portuguese Foundation of Science and Technology (FCT), in its State Budget component (OE) through the projects POCI-01-0145-FEDER-032466 (PTDC/EME-EME/32466/2017), UIDB/00481/2020, UIDP/00481/2020 and CENTRO-01-0145-FEDER-022083- Centro Portugal Regional Operational Programme (Centro2020), under the PORTUGAL 2020 Partnership Agreement, through the European Regional Development Fund. R Santos thanks the support given by CEFET/RJ. The support of General Motors and U. S. Steel for supplying the material is gratefully acknowledged. Especial thanks are expressed to Prof. Frederic Barlat for providing the numerical code for the identification of the coefficients of Yld2000-2d yield function.

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