BEHAVIOR AND FORMING LIMIT DIAGRAM PREDICTIONS OF STAINLESS STEELS SHEETS

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Abstract

The development of adapted design tools and the use of finite element analysis (FEA) for the forming simulation have helped to increase the use of stainless steels in automotive or other applications like appliances. The behaviour in forming can be well described by the knowledge of a stress-strain curve and the anisotropy of the material, especially in the case of ferritic grades or stable austenitic grades. In the case of unstable austenitic grades an other effort was undertaken to propose a behavior model for the transformation induced plasticity (TRIP)- effect. In fact, strain-rate and consequently temperature gradient may have a significant influence on the hardening of unstable stainless steels and consequently on their forming and crash behavior. The thermo-metallurgical-mechanical model uses a minimum number of parameters: form transformation kinetic and strain-stress curves, determined in isothermal conditions. The proposed model did not lead to any restriction on the description of the strain-stress law and consequently could be easily implemented in FEA software. For fracture prediction, Forming Limit Diagrams (FLD) are now in widespread use to evaluate the feasibility of a stamped part. However, they still present the major drawback of a test-intensive determination procedure. In particular, experimental FLD needs to be determined for each thickness, different strain path and finally be reproduced to evaluate the scattering. The author presents a Cayssials-type analytical model, which describes FLD as a strain instability during biaxial loading and permits to predict it from strain hardening properties. Ultimately, the knowledge of mechanical properties, anisotropy and the thickness of the sheet are simply required for an accurate FLD prediction.

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Behavior model for Unstable Austenitic Steels

Trip-Effect

The figure 1a shows conventional tensile curves of unstable austenitic stainless steels for different testing conditions and exhibit two main features :

- an non-constant strain hardening coefficient, leading to some difficulty in fitting such curve with the classical Hollomon or Ludwig models.
- a strong temperature and strain rate sensitivity .

The mechanical behavior of Austenitic stainless steel is linked to austenite stability. Under certain circumstances, the austenite phase has the capability to transform itself into martensite when it is deformed. This metallurgical transformation leads to a particular mechanical behavior designated as the TRIP effect (TRansformation Induced Plasticity). As is the case for most metallurgical transformations, any temperature variation can influence the transformation rate. Consequently, the TRIP-effect has to be taken into account for the modeling of forming and crash behavior.

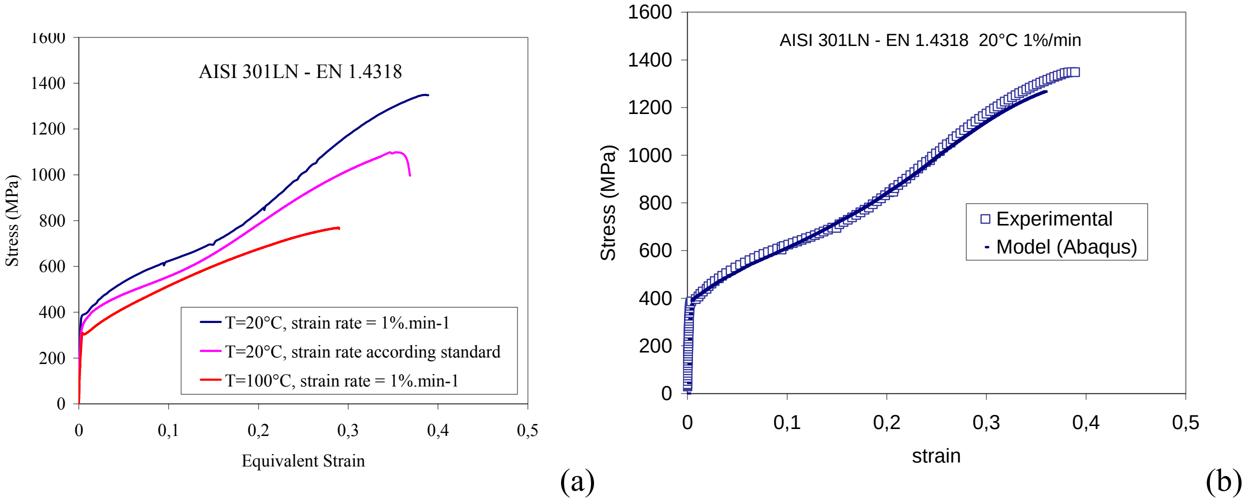

Figure 1: (a) strain-stress curves on a 1.4318 unstable austenitic grade
(b) comparison between the proposed model and the experiment

The proposed model

In order to simulate the TRIP-effect, a model has been developed by ArcelorMittal Stainless that couples both metallurgical and thermo-mechanical laws:

- kinetics of the martensite transformation induced by the deformation (metallurgical aspect); using Olson&Cohen or Guimaeres equations which relate martensite fraction to the strain and temperature.
- thermal equations describing latent heat generated by the transformation, the plastic work transforming into heat.
- mechanical equations of behavior of a micro-structures containing both austenite and α'-martensite by the use of a mix-law.

The development of such a model was performed using an original isothermal tensile test on gridded specimens. So different levels of strain are reached on the same specimen for a given temperature. The martensite content is evaluated measuring the saturation magnetism on small cuts of tensile sample. The model, well described in [1] can be easily implemented into CAE/CAD software. It was done using ABAQUS (Fig. 2b) but also with other codes in the framework of New Generation Vehicle Project [2].

Forming Limit Diagram Prediction

Introductive comments

In a drawing process, the strain state is used to characterize the forming path up to the fracture. Considering conservation of the volume during plastic deformation, the strains in the plane of the sheet, ε_1 and ε_2, are used to characterize this state, and the thinning could be easily deduced. In a diagram (ε_1, ε_2), several deformation modes are encountered. Assuming $\varepsilon_1>0$ for symetry reasons, we have to deal with three locii:

- The drawing area $\varepsilon_2<0$
- Plan strain path $\varepsilon_2 =0$
- The stretching area $\varepsilon_2>0$

The Forming Limit Diagram (FLD) gathers the curves in each domain that separate the safe area during the forming from an area where necking appears and leads to the fracture of sheet. From a practical point of view, the determination of a FLD is very time and cost consuming. Indeed, several deformation tests corresponding to different deformation modes (different ratio $\rho=\varepsilon_1/\varepsilon_2$) have to be performed to determine it (Fig.2). Consequently, many models dedicated to FLD's prediction have been developed. A Cayssials-type model was developed at ArcelorMittal and adapted to stainless steel [3] and it is summarized in the following paragraph.

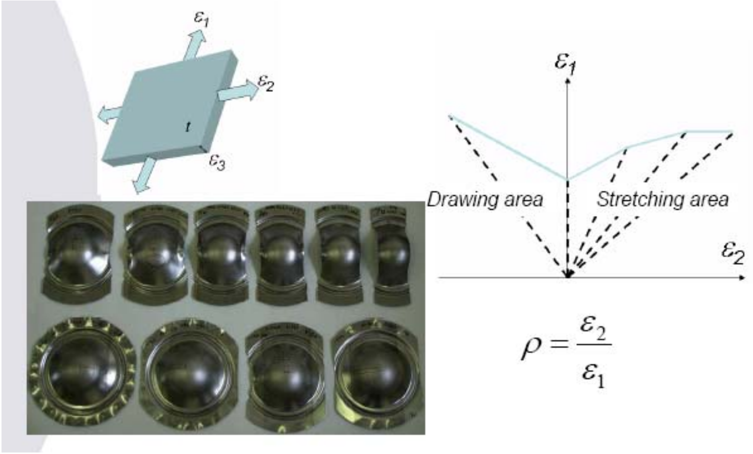

Figure 2: Forming limit diagram principle and Nakazima experimental method for its determination

Proposed FLD model

In the drawing area, the necking boundary is determined by using the instability plastic theory assuming viscoplastic material and necking band occurance (after Hill 1952, Duncombe 1974, Dudzinski & Molinari 1998). For a given path, ε_1 is a function of the hardening coefficient n and ε_{10} value at $\varepsilon_2 = 0$ given by the relation $\varepsilon_{10} = a.n + b.m.t$, where t and m are respectively the thickness and strain rate sensitivity coefficient, a and b two constants to be indentified. In the stretching area, the mechanism of necking is different and we used the plastic deformation theory, i.e. elastoplasticity with vertex effect and occurance of strain rate gradient jump in the necking band(after Storen & Rice 1975, Hutchinson & Neale 1978). The anisotropy effect in the stretching area was introduced later by Cayssial. Finally the model takes into account four parameters:

- The hardening coefficient (*n*-value): this coefficient is the most important coefficient: an increase of the *n*-value raises the level of the FLD
- The rate sensitivity coefficient (*m*-value): this coefficient has a similar effect as the hardening one, but is less important
- The Lankford parameter (*r*-value): this coefficient has an effect of the second order; when the *r*-value increases, the performances in the stretching area decrease.
- The thickness: an increase of the thickness of the sheet leads to a raise of the FLD's level.

Relation with the measured quantities

Due to different ways of determination of the mechanical properties of ferritic and austenitic stainless steels, the coefficients of the model are different for the two families of grades. In the case of unstable austenitic grades with a strong TRIP-effect, we showed previously that the hardening coefficient cannot be determined easily. On the other hand, it is well known that the necking appears at $\varepsilon = n = \ln(1+Ag)$ where Ag is the uniform elongation used in the model rather than the *n*-value. Concerning the rate sensitivity coefficient m, it can be computed from the Tensile strength Rm values by $m = A.Rm^{-B}$. Finally, the constants a, b, A and B are identified by calibration tests; the model depends on Rm strength, Ag strain value, r-value and the thickness t.

Comparison between the model and experiences

We can see in Figure 3 that the Cayssials-type model provides a good prediction of the FLD level. Indeed, for the austenitic grades, 8 cases have been tested (different grades, with different thicknesses). For these 8 cases, we obtained 85% of results with an error lower than 0.03 for the major strain and 92.5% of results with an error lower than 0.05. Concerning the ferritic grades, 7 cases have been tested. For these 7 cases, we obtained 80% of results with an error lower than 0.03 for the major strain and 100% of results with an error lower than 0.05.

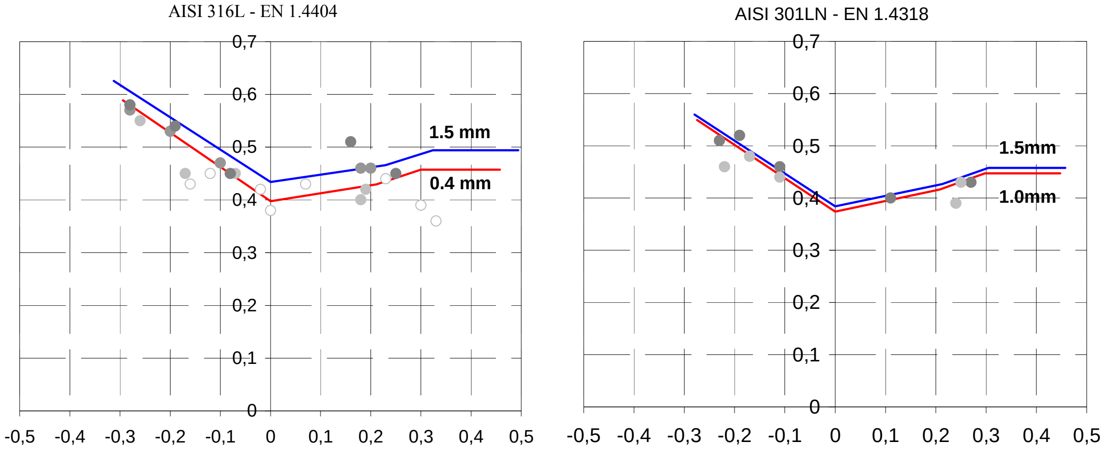

Figure 3: comparison between model and experimental FLD

Conclusion

The proposed model permits to evaluate FLD from tensile test parameters in the 3 directions of the sheet and leads to an accurate prediction. Today we use this predictive model to draw the FLD when it is not available experimentally in our database or when the deadline is too short to performe the characterization. There is still some room for improvement, especially in the case of thin strip (thickness typically less than 0.2mm) because the hypotheses of the model are no longer valid when the thickness becomes of the order of several grain or inclusion sizes, and so the thickness effect is not well described. Moreover, it has been shown in the first part of this paper that unstable austenitic grades are sensitive to the strain rate and even if at this stage we are able to reproduce this behaviour, the sensitivity of the FLD, and more generally of the fracture criterion, is not fitted today with the performed calibration tests.

References

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