

Determination of the yield locus by means of temperature measurement

D. Banabic¹, J. Huetink²

¹ *Technical University of Cluj-Napoca, C. Daicoviciu 15, 400020 Cluj-Napoca, Romania*
URL: <http://www.utcluj.ro> e-mail: banabic@tcm.utcluj.ro

² *University of Twente, P.O. Box 217, 7500 AE Enschede, Netherlands*
URL: <http://www.tm.ctw.utwente.nl> e-mail: j.huetink@utwente.nl

ABSTRACT: The paper presents a theoretical background of the thermo-graphical method of determining the yield locus. The analytical expression of the temperature variation of the specimen deformed in the elastic state is determined starting from the first law of thermodynamics. The experimental method for determining the yield locus based on the Joule-Thompson effect is presented in detail. The analytical model is validated by experiments. Based on these results, it is theoretically justified that the Joule-Thompson effect can be used in the experimental determination of the yield locus. The thermo-graphical method has been used to determine the yield locus of the AA 5182-0 aluminium alloy.

Key words: material experiments, yield locus, sheet metal, Joule-Thompson effect

1 INTRODUCTION

The yield locus must always be taken into consideration in the metal forming processes analysis. It defines the boundary between the elastic and plastic deformation and can be defined by an implicit function (yield function) of the components of the stress tensor. Yield functions are used in describing mathematical models of the forming processes. Many such functions have been determined over the years, especially in order to describe the anisotropic behavior of sheet metals (see more details in [1], [2]). In order to validate them one must compare their predictions with the experimental results. Even though the experimental determination of the yield loci is very expensive and difficult, its necessity is undeniable.

Scientists have developed more and more sophisticated and precise experimental methods to determine the yield loci. The transition of materials from elastic to plastic behavior is associated to different phenomena, such as: remnant deformation, thermal emission, acoustic emission, variation of the electron work function (EWF), alteration of the Moire patterns etc. By tracking any of these companion phenomena one can determine a boundary physical parameter (elongation, temperature, acoustic emission intensity, electron work function etc.). This boundary value is determined from the variation curve of the tracked

parameter and corresponds to a critical point (minimum, maximum, inflexion, corner etc.). A review of these methods is presented in [3].

In the following we will focus on the yield locus determination method based on thermal emission. By analogy with gas expansion (Joule-Thompson effect), the specimen deformation in the elastic state leads to its cooling. This phenomenon can be proved starting from the first law of thermodynamics (see [4]). The deformation of the specimen while it is in plastic state leads to its warming. This phenomenon has first been observed by Tresca in 1870 [5]. More thorough research in this field has been initiated by Farren and Taylor [6] and Taylor and Quiney [7]. Therefore, by continuous loading of the specimen, starting from a null loading state, one will first observe a decrease in temperature (while the specimen is still in the elastic state), followed by an increase in temperature (corresponding to the plastic state). In the hypothesis of a linear dependence of the temperature with respect to elongation in both cases, the intersection of the two segments will be the boundary point between the two states. Gabryszewski [8] first used this method for the determination of the yield stress in the case of the uniaxial tensile test. The method has been extended for the biaxial tensile test for the determination of the yield locus by Sallat [9] and it was improved by Müller [10], Müller and Pöhlandt [11] and Banabic et al [12].

2 THEORETICAL BACKGROUND

The method of determining the yield loci based on the temperature variation during the deformation process has been used without a thorough theoretical background. This background is given in this section and it is shown that the measured maximum temperature decrease in the elastic area before yielding is in the range that can be expected from the theory. For the sake of convenience the following elaboration is restricted to small deformations and isotropic material properties.

The first law of thermodynamics can for reversible processes be written as:

$$\rho \dot{e} = \boldsymbol{\sigma} : \mathbf{d} + \rho r \quad (1)$$

where ρ is the mass density, \dot{e} is the change in the internal energy, $\boldsymbol{\sigma}$ is the Cauchy stress, \mathbf{d} is the rate of deformation, and r is a heat source.

For small (infinitesimal) displacements it holds that $\mathbf{d} = \dot{\boldsymbol{\varepsilon}}$, where $\boldsymbol{\varepsilon}$ is the (elastic) strain. The supplied heat ρr is for reversible processes: $\rho r = \rho T \dot{s}$, where T is the absolute temperature and s the entropy.

With these conditions the first law becomes:

$$\dot{e} = T \dot{s} + \frac{1}{\rho} \boldsymbol{\sigma} : \mathbf{d} \quad (2)$$

As e can be regarded as a function of s and $\boldsymbol{\varepsilon}$, the next equation holds:

$$\dot{e} = \left(\frac{\partial e}{\partial s} \right)_{\boldsymbol{\varepsilon}} \dot{s} + \left(\frac{\partial e}{\partial \boldsymbol{\varepsilon}} \right) : \dot{\boldsymbol{\varepsilon}} \quad (3)$$

hence,

$$T = \left(\frac{\partial e}{\partial s} \right)_{\boldsymbol{\varepsilon}} \text{ and } \boldsymbol{\sigma} = \left(\frac{\partial e}{\partial \boldsymbol{\varepsilon}} \right) \quad (4)$$

and consequently (Maxwell relation)

$$\left(\frac{\partial T}{\partial \boldsymbol{\varepsilon}} \right)_s = \left(\frac{\partial \boldsymbol{\sigma}}{\partial s} \right)_{\boldsymbol{\varepsilon}} = T \left(\frac{\partial \boldsymbol{\sigma}}{\partial T \partial s} \right)_{\boldsymbol{\varepsilon}} = T/c_v \left(\frac{\partial \boldsymbol{\sigma}}{\partial T} \right)_{\boldsymbol{\varepsilon}} \quad (5)$$

The last term is obtained by considering that at a constant volume it holds that: $(T ds)_{\boldsymbol{\varepsilon}} = (c_v dT)_{\boldsymbol{\varepsilon}}$. In solids compressive stresses are observed at heating while keeping the volume constant (suppressing thermal expansion). Consequently, during a tensile test, the last term in Eq. (5) is negative, and hence

$$\left(\frac{\partial T}{\partial \boldsymbol{\varepsilon}} \right)_s < 0 \quad (6)$$

Hence in a tensile test the temperature decreases as long as the deformation is elastic (the J-T inversion temperature is much higher than the room temperature).

For isotropic materials the linearised expression for the stress is:

$$\boldsymbol{\sigma} = C_b (\text{tr}(\boldsymbol{\varepsilon}) - \alpha_v \Delta T) \mathbf{1} + 2G(\boldsymbol{\varepsilon} - 1/3 \text{tr}(\boldsymbol{\varepsilon})\mathbf{1}) \quad (7)$$

Substitution of (7) in (5) yields:

$$\left(\frac{\partial T}{\partial \boldsymbol{\varepsilon}} \right)_s = \frac{T}{\rho c_v} (-\alpha_v C_b + \frac{dC_b}{dT} (\text{tr}(\boldsymbol{\varepsilon}) - \alpha_v \Delta T)) \mathbf{1} + 2 \frac{dG}{dT} (\boldsymbol{\varepsilon} - 1/3 \text{tr}(\boldsymbol{\varepsilon}) \mathbf{1}) \quad (8)$$

Neglecting a temperature dependency of the bulk modulus and shear modulus leads to a temperature change (under adiabatic conditions):

$$\Delta T = \left(\frac{\partial T}{\partial \boldsymbol{\varepsilon}} \right)_s : \Delta \boldsymbol{\varepsilon} = -\frac{T}{\rho c_v} \alpha_v C_b \text{tr}(\Delta \boldsymbol{\varepsilon}) \quad (9)$$

The following is an example of the application of the above equation for an aluminium alloy. Typical values for the thermal expansion coefficient, bulk modulus, specific heat and density are: $\alpha_v = 70 \cdot 10^{-6} / \text{K}$, $C_b = 0.68 \cdot 10^{11} \text{ N/m}^2$, $c_v = 904 \text{ J K/kg}$, $\rho = 2650 \text{ kg/m}^3$. The maximum elastic volume increase is about $\text{tr}(\boldsymbol{\varepsilon}) = 0.0007$. Hence, at room temperature (293 K), we obtain a temperature decrease $\Delta T = -0.4 \text{ K}$.

3 EXPERIMENTS

The thermo-graphical method for the experimental determination of the yield loci is successfully used in the Institute of Metal Forming Technologies from Stuttgart University. The following paragraphs briefly describe this method.

By varying the longitudinal and transverse forces acting on a cross tensile specimen (see Fig. 1) any point of the yield locus in the range of biaxial tensile stress can be obtained. A description of the cross tensile specimen, which has been optimised by means of stress optical methods such as to obtain a zone of homogeneous stress can be found in Kreissig [13].

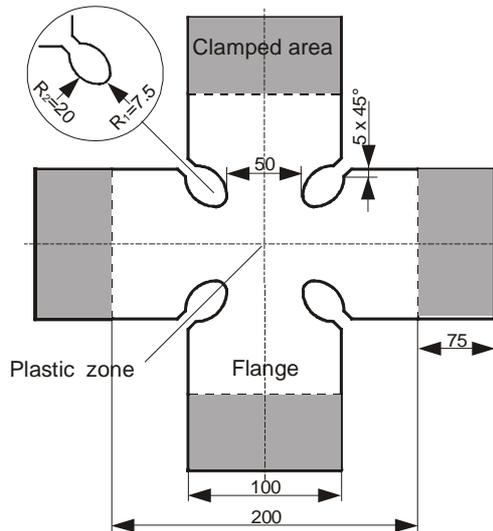


Figure 1 Cruciform specimen for the biaxial tensile test

Starting from this geometry, a further optimisation was carried out whereby, besides a zone of homogeneous stress, a large strain is obtained before instability occurs in the notches. For this purpose, the geometrical parameters shown in Figure 1 were varied. Since the optimum geometry depends to some extent on the material properties, it was verified by stress optical experiments that for the dimensions used there is a large zone of homogeneous biaxial stress [10]. The problem of the „equivalent cross section“ of the specimen, i.e. the cross section by which the acting force has to be divided for obtaining the true stress has also been addressed in [10].

It was shown that a good accuracy in the determination of the yield loci of materials in the initial state without pre-straining can be achieved by using the nominal cross section from the workshop drawing. In this paper, results are reported of a series of biaxial tensile tests carried out on cruciform specimens of AA5182-0 aluminium alloy sheet metal (1.0 mm thickness) using a CNC stretch-drawing facility (Fig. 2).

The beginning of the plastic yielding was monitored by temperature measurements using the Sallat method [9]. The temperature of the specimen was measured by an infrared thermo-couple positioned at an optimised distance from the specimen (see Fig. 2).

The optimised distance has been choosing by trial and error method. During elastic straining, the specimen's temperature decreases by a fraction of a degree due to thermo-elastic cooling. When plastic flow begins, the temperature rises strongly (Fig. 3).

In contrast to 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, the values of

the yield stresses obtained with this method are

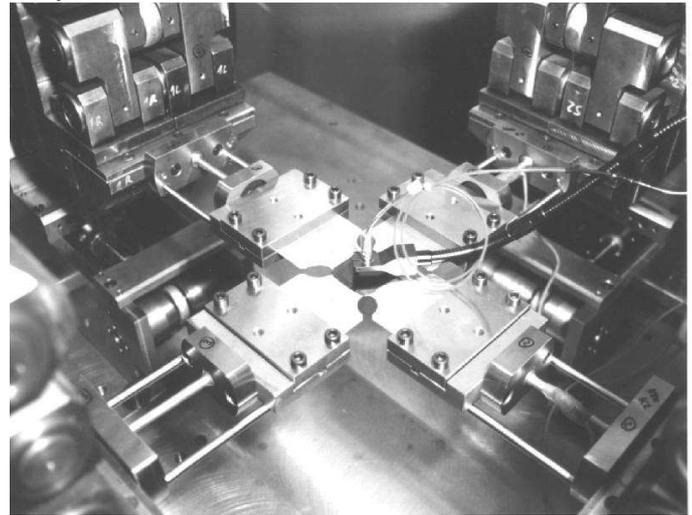


Figure 2 Biaxial tensile test device for cross specimens

smaller than the values obtained using the classical method, i.e. stress gauge measurements, because the “offset elongation” is smaller than 0.2% (see Fig. 3). The yield points corresponding to seven different ratios of the applied load: 1:0, 4:1, 2:1, 1:1, 1:2, 1:4, 0:1 were measured (all the points are in the first quadrant). The experimental yield locus for AA 5182-0 aluminium alloy is shown in Figure 4.

4 VALIDATION

Even though the thermo-elastic effect is relatively small and is usually neglected in metal forming processes analysis, it can be detected and used in the experimental determination of the yield loci. Experiments made on different aluminium alloys (i. e. AA 5182-0) have proven a decrease of the temperature of the specimen by approximately

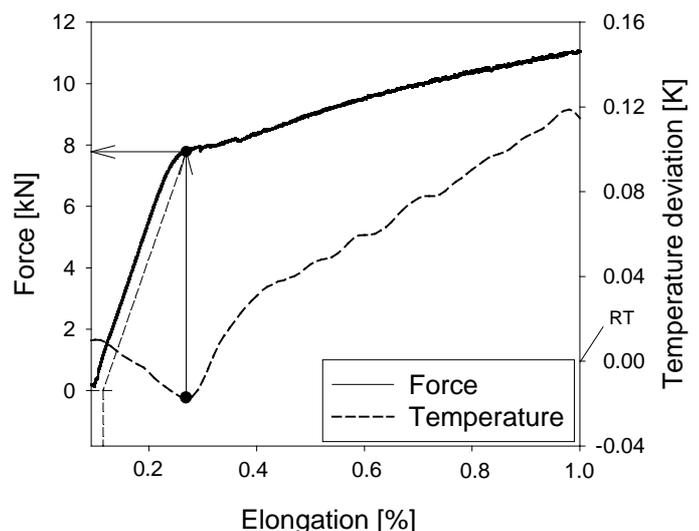


Figure 3 Force and temperature deviation from room temperature (RT) versus elongation

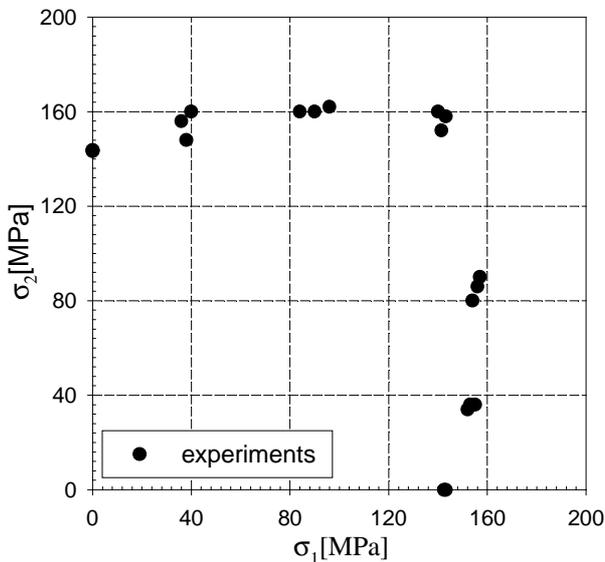


Figure 4 Yield locus experimental data for AA5182-0 alloy

0.024 K, while analytical models predict a decrease of 0.40 K. The difference between the two values could be attributed to the following facts: the experiment is not exactly adiabatic and hence there is some heat loss; the analytical model is rough, and does not account for conduction due to an inhomogeneous deformation and temperature distribution; the thermal and mechanical parameters of the tested material are rough. The measured temperature decrease reported in [11] is 0.25 K for another aluminium alloy and is in close agreement with the theoretical value. The difference between the results in paper [11] and the ones in this paper are due to the different strain rates of the specimen. The Müller and Pöhlandt experiments [11] have been carried out much faster than the ones presented in paper. The experiments should be carried out fast to reduce the heat loss. Note that the temperature decreases during the elastic deformation only if the specimen volume increases.

The thermo-graphical method has been successfully used to determine the yield locus of the AA 5182-0 aluminium alloy.

CONCLUSIONS

The thermo-graphical method used for the experimental determination of yield loci for sheet metals has only been used empirically so far. The theoretical basis of this method is presented in this paper. The analytical equation of the temperature variation with respect to the physical parameters of the material and volume variation of the specimen during the elastic deformation is determined starting

from the first principle of thermodynamics. Even though the analytical model is very rough, it can describe, from the qualitative point of view, the temperature decrease during the elastic deformation of the specimen. From the quantitative point of view, there are significant discrepancies between the predicted and experimental values.

The results presented in this paper prove, from the theoretical point of view, the possibility of determining experimentally the yield locus by using the thermo-graphical method. Experiments made on the AA 5182-0 aluminium alloy yield locus have proven the validity of the thermo-graphical method.

REFERENCES

1. D. Banabic, H.J. Büнге, K. Pöhlandt, A.E. Tekkaya, *Formability of Metallic Materials*, ed. D. Banabic, Springer Verlag, Berlin-Heidelberg (2000).
2. F. Barlat, O. Cazacu, M. Zyczkowski, D. Banabic, J.-W. Yoon, Yield surface plasticity and anisotropy, In: *Continuum Scale Simulation of Engineering Materials Fundamentals-Microstructures-Process Applications*, eds. D. Raabe, L.-Q. Chen, F. Barlat and F. Roters, Wiley-VCH, Berlin (2004) 145-185.
3. D. Banabic, Experimental methods for determining the yield loci (will be published)
4. G. Backhaus, *Deformationsgesetze*, Akademie Verlag, Berlin (1983).
5. J. Bell, *The Experimental Foundation of Solid Mechanics*, Springer Verlag, New-York (1973).
6. W.S. Farren, G.I. Taylor, The Heat developed during plastic extension of metals *Proc. Royal Soc., Series A* 107(1925) 422-451.
7. G.I. Taylor, M.A. Quiney, The Latent heat remaining in a metal after cold work *Proc. Royal Soc., Series A* 143(1934) 307-326.
8. Z. Gabryszewski, W. Srodka, Zastosowanie temperatury sprzezonej z odkształceniami do oceny dysypacji energii i wyznaczania granic plastycznosci, *Mechanica Teoretyczna i Stosowana* 19(1981).
9. G. Sallat, *Theoretische und experimentelle Untersuchungen zum Fließverhalten von Blechen im zweiachsigen Hauptspannungszustand* Diss. TU Karl Marx Stadt (1988).
10. W. Müller, *Beitrag zur Charakterisierung von Blechwerkstoffen unter zweiachsiger Beanspruchung*, Diss. Universität Stuttgart, Springer-Verlag, Berlin (1996).
11. W. Müller, K. Pöhlandt, New experiments for determining yield loci of sheet metal, *Journal of Materials Processing Technology* 60(1996) 643-648.
12. D. Banabic, D.S. Comsa, S. Keller, S. Wagner, K. Siegert, An yield criterion for orthotropic sheet metals, In: *Innovations in processing and manufacturing of sheet materials*, ed. M. Demeri, TMS, Warrendale, (2001) 145-159.
13. R. Kreißig, *Theoretische und experimentelle Untersuchungen zur plastischen Anisotropie* Diss. TU Karl-Marx-Stadt (1981).