Experimental and numerical investigation of the formability of an ultra-thin copper sheet

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Abstract. The aim of this study is to investigate the forming limits of an ultra-thin copper sheet (0.1mm thickness) that is used for connection applications. The first step consists in characterising the mechanical behaviour under different strain paths, up to necking and final rupture, such as uniaxial and biaxial tension, in order to investigate the largest range of triaxiality ratios for this material. Nakazima tests are performed on specific samples with a designed-on-purpose device in order to determine experimentally the onset of rupture. Strain distribution over the surface in tension is measured with digital image correlation technique. The forming limits are characterised experimentally for different strain paths and compared to predictions given by macroscopic fracture criteria. It is shown that when the macroscopic criterion involves a sufficient number of parameters, it is able to predict limit forming curves with a reasonable accuracy.

1. Introduction
Micro-forming processes of ultra-thin metal sheets present many challenges from the industrial and academic point of view. For example, in progressive die forming processes, numerical validation of the parameters of drawing or assembly processes requires the taking into account of the material limits, like necking and rupture that is usually performed by using forming limit curves. However in many cases, using these curves is no longer possible since the bending over small radius. The aim of this study is to investigate the forming limits of an ultra-thin copper sheet (0.1mm thickness) that is used for connection applications, considering macroscopic fracture criteria.

According to Fu and Chan [1], ductile failure criteria can no longer be used to predict the rupture of ultra-thin sheets when the size of the manufactured parts decreases. Indeed, for such sheets, it is observed that the rupture occurs prematurely during tensile tests, or that the fracture strain is less than that of conventional thin sheets (typically of the order of 1 mm). For example, the evolution of the fracture-to-thickness strain in copper alloys has a non-linear shape, often represented by a logarithmic curve. When the thickness of the sheet becomes less than 0.15 mm, the fracture strain drops drastically [2].

Observations of the microstructure of the fracture surface of ultra-thin tensile samples show that the rupture mode evolves from ductile fracture to brittle fracture at its ultimate stage. The decrease in the fracture strain of the ultra-thin tensile specimens is explained by the small number of grains in the thickness. Dimples, caused by void growth, usually appear at the grain boundaries or at the inclusions of inner grains [3]. When the thickness of the sheet decreases, the number of inner grains and boundaries decrease, which causes a reduction in the
number of voids sites on the fracture surface. Moreover, due to the limited number of grains in the thickness, individual properties of each grain (orientation, mechanical behaviour, size, etc.) become preponderant, which facilitates shear deformation and slip systems between grains [3, 4].

In a first step, the mechanical behaviour is characterised under different strain paths, up to necking and final rupture, such as uniaxial and biaxial tension, in order to investigate the largest range of triaxiality ratios. Nakazima tests are performed on specific samples with a designed-on-purpose device in order to determine experimentally the onset of rupture. Strain distribution over the surface in tension is measured with digital image correlation technique. The forming limits are determined using several sample geometries and are compared with macroscopic fracture criteria.

2. Material
The studied material is a cold rolled sheet of 0.1 mm thick of copper 99.9% pure (according to Goodfellow supplier). Quantitative information on the microstructure is obtained from Electron BackScatter Diffraction (EBSD) scans in the rolling and transverse direction sections and it is observed that the texture is weakly marked. The average grain size is 10 µm with a maximum of 140 µm. The dispersion on the grain size is low with an average of 10 grains in the thickness. In order to investigate the sheet behaviour under different strain paths, three types of mechanical tests were performed, namely tensile tests, monotonic and Bauschinger shear tests and balanced biaxial expansion. The strain field is measured using Digital Image Correlation (DIC) system Aramis (GOM GmbH). The procedure is detailed in [5, 6], and a plot of all the stress-strain curves is presented in Fig.1.

3. Experimental procedure and results
Several methods exist to determine the forming limit curve (FLC) of a given material [7] by the occurrence of a localised thinning (necking) or a rupture, according to the strain state. Among these methods, that proposed by Nakazima with a hemispherical punch and rectangular specimens of different widths is chosen in this study. This type of test makes it possible to obtain the evolution of strain both in shrinkage or in expansion areas of sheet metal forming. A designed-on-purpose device is developed to perform Nakazima tests on a Zwick BUP 200 stamping machine. A reduced scale of the ISO 12004-2:2008 standard [10] is used for all tools and samples. The dimensions of the tools are presented in Fig.2. During the tests, the blank-
holder force is kept constant at 23 kN in order to ensure full clamping of the samples. The punch moves at a constant speed of 0.25 mm.s\(^{-1}\) to deform the specimen until it breaks.

![Image](image1.png)

**Figure 2.** Geometry of the designed-on-purpose Nakazima device (left part) and dimensions of the samples for ultra-thin sheet characterisation (right part). 1. Punch - 2. Blank-holder - 3. Centering pins - 4. Die - 5. Blank

In order to obtain different strain paths, the gauge area of the sample is a rectangle of 17 mm long which width varies from 5 mm to 65 mm. One drawback of the Nakazima test is the friction between the punch and the sample that often leads to fracture outside the pole, that tends to decrease the level of FLCs compared to other methods. To reduce the friction effect, a teflon sheet of 0.05 mm is bonded to the inner surface of the specimen via a layer of grease. After several trials, this method makes it possible to obtain the rupture at the pole of the samples, whatever the geometries.

![Image](image2.png)

**Figure 3.** Evolution of major and minor strains as a function of the width for a selected section just before fracture

The punch force and punch displacement are recorded during the test and the curves are plotted for each configuration to check the reproducibility. At least 5 tests have been performed for each geometry of sample. The acquisition frequency of the DIC system is set to have fewer
images at the beginning of the test (2 frames per second) and then it is increased up to 20 frames per second during necking and rupture. Each image is processed by the DIC system to measure the strain tensor components. Thanks to this high acquisition frequency, the deformation just before rupture can be recorded.

The ISO 12004-2:2008 standard [10] is used to determine necking and fracture points by 3D optical measurement in the Nakazima test. For each sample geometry, three parallel sections perpendicular to the rupture are defined with a distance of 1.5 mm between them and the strain along each section is plotted for each image. A sudden increase in the major and minor strains between two successive instances is characteristic of the rupture and the image obtained just before fracture is chosen according to Fig.3. The maximum value of the major strain defines the fracture strain of the specimen. From this point, boundaries of the necking zone can be determined by the values of $l_0$, $W_g$ and $W_d$ (see Fig.3) either by a second derivative of two sections (according to this standard), or by imposed values (equal to 5 using the same scaling factor with the values given by this norm). The points included in the zones defined by $W_g$ and $W_d$ are used to fit an inverse second-order polynomial, which vertex defines one point of the FLC as presented in Fig.4.

![Fracture forming limit curve for the pure copper ultra-thin sheet and corresponding images of the different geometries of samples at rupture](image)

**Figure 4.** Fracture forming limit curve for the pure copper ultra-thin sheet and corresponding images of the different geometries of samples at rupture

It has to be noticed that using this method, FLCs issued from necking points or directly from fracture points could be determined. For this material, the points measured for necking and rupture were coincident or very close for most strain paths, since fracture was observed as soon as necking starts. This phenomenon is typical of ultra-thin sheets: as the thickness of the material decreases, the percentage of necking strain decreases, and the range of diffuse necking diminishes. At a macroscopic scale, this leads to a brittle-like behaviour which is a consequence of the vanishing of necking, since the orientation of the crack changes as well with miniaturisation (see e.g. [11]). But the material can not be considered as fully brittle either, since its plastic deformation is quite large and the observation of its fracture surface shows a failure in shear without dimples. Fracture FLC is then considered for the remaining part of this study, making pertinent to use macroscopic rupture criteria.

The FLC presented in Fig.4 is consistent with previous results obtained from similar materials. In [12], the forming limit curves of pure copper were investigated using Nakazima tests for several sheet thicknesses. As the sheet decreases to 0.1 mm, the FLCs are shifted down to a major strain...
in tension of 0.2, which is very close to our results. It has to be noticed that when thicker sheets are considered, the lowest point of the FLC (in plane tension) can reach values larger than twice the value obtained for the lowest thickness. In a more recent work, [13] investigated the FLC of copper alloy using Marciniak tests and the results are similar, despite the difference in thickness.

4. Constitutive behaviour and macroscopic rupture criteria
The constitutive behaviour is elastic-plastic with isotropic hardening associated with the Hill 48 yield criterion. Elastic behaviour is defined by the Hooke’s law, the Young modulus is $E = 136$ GPa and the Poisson’s ratio $\nu = 0.34$. The isotropic hardening is described by the Voce relation: $\sigma = \sigma_0 + Q(1 - \exp(-b\bar{\epsilon}_p))$, with $\sigma_0$, $Q$ and $b$ material parameters determined from a tensile test in the rolling direction. $\bar{\epsilon}_p$ defines the equivalent plastic strain. The material parameters $R_{ii,i=1..3}$ are deduced from the plastic anisotropy ratios ($r_0$, $r_{45}$, $r_{90}$), calculated from tensile test data for 3 different orientations (0, 45 and 90° to the rolling direction).

| $\sigma_0$ | $Q$ | $b$ | $R_{11}$ | $R_{22}$ | $R_{33}$ | $R_{12}$ | $R_{13}$ | $R_{23}$ |
|-----------|-----|-----|---------|---------|---------|---------|---------|---------|
| 243       | 108 | 3.8 | 1.000   | 1.006   | 0.911   | 0.984   | 1.000   | 1.000   |

Table 1. Material parameters of the constitutive law (Values of $\sigma_0$ and $Q$ are in MPa)

In order to predict the rupture of the samples, two macroscopic rupture criteria are studied, namely Ayada [8, 9] and Lou et al. [14]. For the first one, fracture occurs when $D_A = D_A^C$ with:

$$D_A = \int_0^{\epsilon_f} \frac{\sigma_h}{\sigma} d\bar{\epsilon}_p$$  \hspace{1cm} (1)

and for the second one, fracture occurs when $D_L = D_L^C = 1.0$ with:

$$D_L = \frac{1}{C_3} \int_0^{\epsilon_f} \left( \frac{2\tau_{\text{max}}}{\bar{\sigma}} \right)^{C_1} \left( \frac{(1 + 3\eta)}{2} \right)^{C_2} d\bar{\epsilon}_p$$  \hspace{1cm} (2)

where $\langle x \rangle = x$ when $x \geq 0$ and $\langle x \rangle = 0$ when $x < 0$. $\bar{\sigma}$ is the equivalent stress, $\sigma_h = \text{tr}(\sigma)/3$ the hydrostatic stress, $\eta = \sigma_h/\bar{\sigma}$ the stress triaxiality, and $C_1, C_2, C_3$ are material constants. $\tau_{\text{max}}$ is the maximum shear stress depending on the Lode angle of the loading path according to the relation given in [15].

Figure 5. Experimental and numerical prediction of FLC for the pure copper ultra-thin sheet with Ayada’s criterion
For Ayada’s criterion, the value of $D_C^A$ is determined from a tensile test. But for ultra-thin sheets, the fracture strain $\epsilon_f$ in tension is often weak due to the high influence of the machining operations. In order to identify its value, the Nakazima test for the geometry close to a tensile test (width 5 mm) is preferred. Then, other strain paths are obtained by the numerical simulations of other configurations. As an example, strain paths obtained in the Nakazima test are plotted in Fig.5 for the two extreme paths, i.e. in the tensile direction (width 5 mm) and in the expansion direction (width 65 mm). The agreement between experimental and numerical results is very good, which confirms the relevance of the numerical model. The fracture strain for a particular strain path is then determined as soon as the criterion is fulfilled, i.e. when $D_A$ is equal to $D_C^A$ its value in the configuration width 5 mm. The values obtained for all strain paths are plotted in Fig.5. With Ayada’s criterion, it is observed that the values in the tensile region of the FLC are well predicted, but this criterion is not able to predict rupture for biaxial expansion and is very poor for all strain paths in the expansion area.

In order to improve the prediction in this area, the criterion proposed by Lou et al. [14] is considered. This criterion requires three different strain states in order to identify the values of the material parameters $C_1, C_2, C_3$, involving both the influence of shear stress and stress triaxiality. Tensile strain state, plane traction and biaxial expansion are retained to identify these values and fracture is determined when $D_L = 1.0$. The calculations are currently in progress, but the first results show that with this latter criterion, the prediction of the FLC will be improved, particularly in the expansion region.

5. Conclusions
This work aims to characterise experimentally and to predict numerically the limits of an ultra-thin copper sheet (0.1mm thickness) that is used for connection applications. In this study, the occurrence of rupture during sheet forming processes considers macroscopic fracture criteria. In a first step, the mechanical behaviour is characterised under different strain paths, up to necking and final rupture, such as uniaxial and biaxial tension, in order to investigate the largest range of triaxiality ratios for this sheet. Nakazima tests are performed on specific samples in order to determine experimentally the onset of rupture and the forming limit curve is plotted. Conversely to classical assumptions on the prediction of rupture of ultra-thin metallic sheets, it is shown that when the macroscopic criterion involves a sufficient number of parameters issued from different triaxiality ratios, it is able to predict forming limit curves with a reasonable accuracy.

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