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Strain path influence on size effects during thin sheet copper microforming

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Abstract: The influence of the size effects on the forming processes for micro-sized parts is not yet well known. This work follows experimental and numerical studies of the effect of a reduction in thickness (t) over grain size (d) ratio on the mechanical properties of high purity copper. Under tensile conditions, copper exhibits softer mechanical properties if $t/d < 6$, in agreement with previous results concerning Al or Ni. To assess the influence of complex loadings linked to forming processes on size effects, Nakazima tests were performed with 20 mm hemispherical punch on a universal sheet metal testing machine associated to a 3D video extensometer. Our results revealed that size effects are strongly sensitive to strain paths. Depending on these latter, the deterioration of the mechanical properties shown for tension is modified.

Keywords: size effects; forming limit diagrams; polycrystalline copper; micro-formability.

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1 Introduction

The increasing demand for powerful miniaturised products for all industrial applications has prompted the industry to develop new and innovated manufacturing processes to mass produce miniature parts minimising material waste. Despite its potential advantages the industrial utilisation of microforming technology is limited. The deformation and failure mechanisms of materials during microforming are not yet well understood and significantly vary from the behaviour of material in conventional forming operations (Geiger et al., 2001; Vollertsen et al., 2006; Molotnikov et al., 2012). It is hence necessary to understand the mechanical behaviour of high-purity metallic materials during the forming of the micro-parts which are used in several industrials domains such as electronic, automotive, aeronautics...

Several studies reported that mechanical properties of metals in tension decrease when the thickness (t) over grain size (d) ratio, equivalent to the number of grains across the thickness, falls under a given value (Miyazaki et al., 1979; Keller et al., 2011). The goal of this work is to analyse if the same tendency can be observed for high purity copper for complex forming loadings. To this end, tensile and Nakazima tests are performed on thin copper sheets, for different t/d ratios and results are discussed.

2 Experimental procedure

High purity polycrystalline Cu (99.99 wt.%) consisting of 0.5 mm thickness rolled sheets were annealed in vacuum at temperatures between 400°C and 800°C and then air cooled in order to obtain various grain sizes corresponding to t/d ratios ranging between 2.6 and

17. A similar crystallographic texture was revealed by Electron Back Scattered Diffraction (EBSD), with a maximal intensity less than 5 multiples of a random distribution (m.r.d). Table 1 summarises the obtained grain sizes and the corresponding t/d ratios for various heat treatment conditions. For each one, the average grain size was computed using four different specimens.

Table 1 Heat treatment conditions and corresponding mean grain size and t/d ratio ($t = 0.5$ mm)

Temperature (°C)	Time (min)	Grain size (μm)	t/d
400	220	29	17
500	220	42	12
600	220	60	8.3
650	220	109	4.6
800	220	165	3
800	360	194	2.6

To cover a large spectrum of strain paths and to limit the number of tests, the following geometries and tests were chosen:

- Test 1: Tensile test on classical dog bone samples.
- Test 2: Punch test on notched blanks to get plane strain conditions.
- Test 3: Punch test on plain circular blanks to get balanced biaxial expansion.

Dog bone shape samples with a gauge section of 25 mm in length and 10 mm in width were tested using an uniaxial tensile machine with a 50 kN load cell at a strain rate of $2 \times 10^{-4} \text{ s}^{-1}$.

Nakazima tests, usually performed with a 100 mm hemispherical punch, were adapted for a 20 mm hemispherical punch in order to approach microforming conditions. The ratio of punch radius on sheet thickness is large enough to assume plane-stress deformation for Nakazima tests. These tests were performed on a universal sheet metal testing machine at a punch-speed of 1 mm/s. Blank-holder force was set to 3,000 N to ensure no sliding of the blank. To reduce the friction effect at the punch/sheet interface, a grease/P.T.F.E/grease sandwich was employed following the standard normalisation (International Standard ISO). In this case the friction is supposed to be low and fracture is expected to occur at the top of the dome.

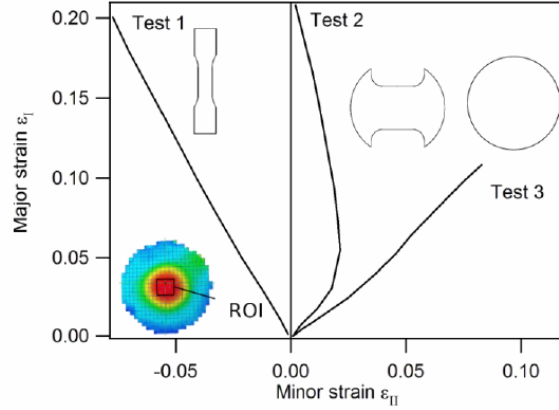
Strain measurements were achieved by a 3D stereoscopy extensometer using Aramis[®] software. A stochastic pattern was sprayed to allow image correlation and strain measurement. True in-plane major (ε_I) and minor (ε_{II}) strains are calculated from $(1 \times 1) \text{ mm}^2$ facet distortion. Thickness deformation $|\varepsilon_{III}|$ is calculated assuming plastic incompressibility. Plastic equivalent strain ε_{eq} is computed using von Mises (VM) formalism:

$$\varepsilon_{eq} = \sqrt{\frac{2}{3}(\varepsilon_I^2 + \varepsilon_{II}^2 + \varepsilon_{III}^2)} \quad (1)$$

Experimental data revealing strain paths (ε_I vs. ε_{II} of centre region for different strain steps) are plotted in Figure 1. Strain measurement reveals that loading is proportional for

test 1 and 3. Strain path of the test 2 begins with an expansion step due to the combined effect of spherical contact between punch and sample, and to the very low flow stress of annealed copper. It is followed by a plane strain step, which was initially expected.

Figure 1 Experimental strain paths for polycrystalline copper samples and corresponding sample geometries (see online version for colours)



Note: Plotted measurements come from the centre of the samples [region of interest (ROI)].

3 Results

3.1 Modification of Hall-Petch law

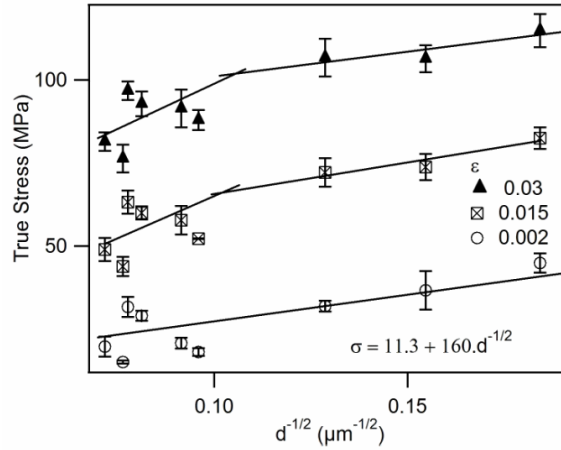
The difference of flow stress level between the specimens with various t/d ratios is classically due to grain size and t/d ratio effects (Keller and Hug, 2008). In order to separate the two size effects, the Hall-Petch (HP) relationship for the grain size dependence of stress [equation (2)] was plotted for different strain levels (Keller et al., 2011).

$$\sigma(\varepsilon) = \sigma_0(\varepsilon) + \frac{k_{HP}(\varepsilon)}{\sqrt{d}} \quad (2)$$

$\sigma_0(\varepsilon)$ is, in first approximation, the yield stress of the single crystal and k_{HP} is a material empirical constant. These parameters depend on strain and this relationship is plotted in Figure 2 for various strain levels. It is shown in Figure 2 that the HP law is respected for the initial yield stress. The σ_0 and k_{HP} values computed using a linear regression are in good agreement with Thompson et al. (1973) ($k_{HP} = 140 \text{ MPa}\cdot\mu\text{m}^{-1/2}$ and $\sigma_0 = 3.4 \text{ MPa}$).

For a strain value of 0.015, two distinct stages are observed: one for samples with less than five grains across the thickness and another for samples with larger t/d ratios in agreement with literature for Cu (Miyazaki et al., 1979; Tabata et al., 1975), Al (Geers et al., 2006) and Ni (Keller et al., 2012). The reduction in t/d for $\varepsilon > 0.015$ results in a strong stress decrease compared to the one expected for the polycrystalline behaviour for the same order of grain sizes.

Figure 2 HP relationship for strains of 0.002, 0.015 and 0.03



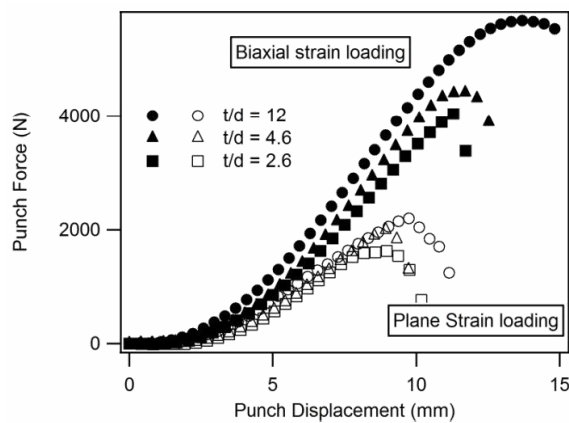
Note: Error bars represent the standard deviation on four tests.

The critical t/d ratio below which occurs the HP breakdown in tension increases with strain until a saturation value around six.

3.2 Nakazima tests

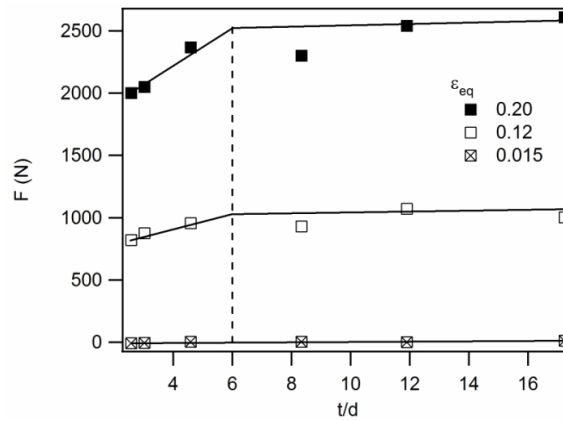
Figure 3 shows the punch force versus punch displacement for different t/d values, for the both complex loadings. As expected, punch force increases with the grain size refinement for both strain paths. For high punch displacements, a gap can be observed between curves obtained for $t/d = 2.6$ and 4.6 in one hand, and curves obtained for $t/d = 12$ in the other hand.

Figure 3 Example of force – displacement curves of Nakazima punch tests for three t/d ratios and two strain paths: plane strain (open markers), biaxial strain (plain markers)



To emphasize this phenomenon, Figure 4 represents the punch force measured for each sample for different equivalent strain of the top sample region (for biaxial strain loading). For low strains, punch force increases linearly with the t/d ratio. As in Figure 2, two trends can be distinguished with a transition for the same critical number of grains across the thickness. The modification of the behaviour appears for a critical equivalent strain level ε_c of 0.12. The same tendency can be observed for the plane strain loading but the apparition of the two hardening regimes occurs for $\varepsilon_c = 0.08$. The critical strain level ε_c which enhances the size effect linked to the decrease in t/d ratio is then strongly strain path dependent.

Figure 4 Punch force in function of t/d ratio for the biaxial strain loading and for different equivalent strain



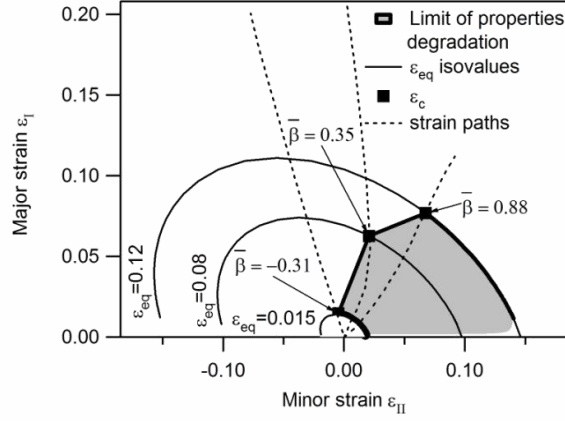
The maximal punch force for the higher t/d ratio is 35% higher than for the specimen with the lowest t/d ratio. This force decrease effect is the same for both complex loadings. In comparison the maximal force is reduced around 10% for tensile conditions.

4 Discussion

The number of grains across the thickness strongly affects the mechanical and forming behaviour of copper thin sheets. Figure 5 summarises the most important results. When the t/d ratio is reduced below six, the stress is reduced independently of the strain path employed in the forming process. This critical t/d value, called $(t/d)_c$, must be considered as a lower bound for the polycrystalline behaviour which ensures a reliable forming process.

The size effect is not only dependent on the grain size or the t/d ratio. It is also relied on the thickness. The $(t/d)_c$ value suggested can be applied for our geometry of samples. A study on the influence of a thickness reduction on this critical value will be published soon, but preliminary results showed that $(t/d)_c$ seems to decrease when the thickness is reduced.

Figure 5 Critical equivalent strain values and corresponding size effects according to the strain paths



However, this phenomenon only appears for a critical equivalent strain ε_c which depends on the strain path. Following our results, ε_c increases with the forming parameter $\bar{\beta} = \varepsilon_{II} / \varepsilon_I$. $\bar{\beta}$ value of each test is an average value for the various t/d samples. It is measured from zero deformation to the critical strain level, when proportional loading is verified. The deviation between measured $\bar{\beta}$ and theoretical values β^{th} could be explained by anisotropic yielding resulting from the initial rolling operation. Assuming plane stress deformation, proportional loading until ε_c and normality of plastic yielding, $\bar{\beta}$ can be linked to stress triaxiality $\bar{\eta}$ via $\bar{\alpha}$ calculation (Marciniak et al., 2002) using the two following relationships:

$$\bar{\alpha} = \frac{\sigma_{II}}{\sigma_I} = \frac{2\bar{\beta} + 1}{2 + \bar{\beta}} \quad (3)$$

$$\bar{\eta} = \frac{\sigma_h}{\sigma_{eq}} = \frac{(1 + \bar{\alpha})}{3\sqrt{1 - \bar{\alpha} + \bar{\alpha}^2}} \quad (4)$$

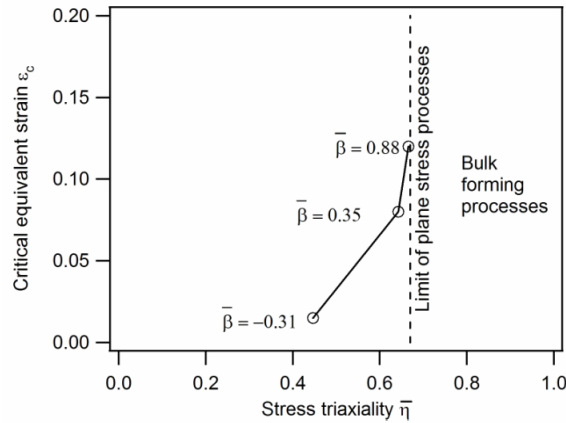
where σ_h is the hydrostatic stress, σ_{eq} the VM equivalent stress, σ_I and σ_{II} are the principal stresses. These different forming parameters are presented in Table 2.

Table 2 Different forming parameters in function of the tests

Theoretical strain path	Stretching	Plane strain	Balanced biaxial expansion
β^{th}	-0.5	0	1
β	-0.31	0.35	0.88
$(t/d)_c$	6	6	6
ε_c	0.015	0.08	0.12
$\bar{\alpha}$	0.22	0.72	0.96
$\bar{\eta}$	0.45	0.64	0.67

Figure 6 represents the evolution of the critical equivalent strain in function of the stress triaxiality. Figure 6 shows that critical equivalent strain increases with the stress triaxiality. As explained in a previous numerical investigation of the miniaturisation size effects in tension (Keller et al., 2012), the stress decrease linked to the reduction in t/d ratio (below the critical value) is due to the formation of stress gradients across the thickness. At surface of samples, the escape of dislocation across the free surface reduces the strain hardening compared to the core of the specimens. The lower is the t/d ratio, the larger is the ratio surface (softer) over bulk (stronger) and the overall flow stress decreases. The effect of the strain path over the t/d ratio effect could be hence due to the modification of the dislocation mean free path which controls the escape of dislocation. For large values of stress triaxiality, several slip systems should be activated compared to tensile conditions, reducing, in turn, the dislocation mean free path and modifying the size effect. Transmission electron microscopy analysis and finite element simulations with crystal plasticity models are in progress to determine the physical mechanisms of these experimental results.

Figure 6 Evolution of the critical equivalent strain which induces size effect as a function of the stress triaxiality of the mechanical test



The strain path dependence of ϵ_c excludes the possibility to generalise the work-hardening law obtained thanks to tensile tests for other strain paths like classically done when isotropic yielding is assumed. This result reveals an anisotropic yielding for t/d lower than six for high purity copper thin sheets. Thin sheet copper forming has consequently to be performed taking into account the t/d ratio effect, which depends on strain path, affecting the punch force and the strain distribution of the forming parts.

5 Conclusions

In conclusion, this work has shown the following results:

- independently of the strain paths, mechanical properties of thin copper sheets are degraded when the number of grains across the thickness is lower than six for $t = 500 \mu\text{m}$

- this modification appears for a critical strain level, which seems dependent on the loading and intrinsically of the stress triaxiality.

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