2D springback and twisting after drawing of copper alloy sheets

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Abstract. This study deals with forming and springback of U-shaped channels made of copper alloy thin sheets. Three materials are considered: pure Cu, copper-beryllium CuBe2 and copper-iron CuFe2P alloys. All these materials are supplied under sheets of thickness around 0.1 mm. Their mechanical behavior is investigated in monotonic uniaxial tension, loading-unloading sequences in tension and simple shear, in order to highlight the hardening, the evolution of the unloading slope with plastic strain and the magnitude of Bauschinger’s effect. Then, drawing of U-shaped elongated parts is performed; to enhance 3D springback, a misalignment of the blank with respect to the punch, die and blank-holder is deliberately applied. The geometry after tool removal is measured by laser scanning, to quantify the magnitude of springback. The twisting parameter, defined as the ratio of the total angle variation between two extreme sections over the distance between the two same sections, is strongly dependent on the material, with a small value of 8° m⁻¹ for CuBe2, an intermediate value of 28° m⁻¹ for pure Cu and a high value of 45° m⁻¹ for CuFe2P. The relationship between 2D springback and twisting is highlighted.

1. Introduction
Virtual design of electronic components for power modules is gaining a growing interest, in order to cope with the antagonist specificities on thermal conductivity and thermal expansion, while keeping good mechanical properties [1]. Materials for substrates are traditionally copper alloys, and more recently, co-laminates in the thickness [2] or in the width. Several forming and cutting steps are necessary to obtain the final structure; the forming steps are dominated by bending and the main issue is related to springback prediction and/or compensation rather than rupture. The prediction of the final shape is essential to ensure the quality and durability of the connections with the components welded or clipped on the substrate.

Springback prediction still demands a validation step, in particular for copper alloys, that have been less addressed in previous investigations. The aim of this paper is to present an experimental database on 2D and 3D springback of copper alloy ultra-thin sheets. It focuses on the springback after forming of elongated U-shaped channels. Springback can be split in 2D springback, corresponding to a change of the section geometry, and twisting. Twisting is characterised by a torsion of the elongated part around an axis parallel to its highest dimension. Previous studies on twisting are mainly dedicated to elongated channels, with straight edges [3] or curved ones, e.g. recently [4,5], with an asymmetry between the left hand side and the right hand side of the U-shaped section. This asymmetry leads to a rotation of the section and its numerical prediction is highly influenced by the mechanical model of the material, in particular there is a significant influence of the unloading slope [5,6]. Using the same experimental rig as
for ultra-thin sheets of stainless steel [3], this study is dedicated to the springback of channels made of copper alloys sheets, with a thickness around 0.1 mm. The next section focuses on the comparison of the mechanical behavior of three copper alloys, namely pure Cu, copper-beryllium and copper-iron alloys, in uniaxial tension and simple shear [7]. Then, original results on the final shape of elongated U-shaped channel, misaligned compared to the tools used for the deep drawing are presented and the influence of the material on springback magnitude is discussed.

2. Materials

Three materials are considered in this study: pure Cu (99.9%) and two alloys, i.e. beryllium-copper (CuBe2) and iron copper (CuFe2P). They are provided as ultra-thin sheets of 0.1 mm for pure Cu and CuBe2 and 0.127 mm for CuFe2P. Though the small thickness, the ratio of the thickness over the grain size lies in-between 10 to 20 [8], ensuring that no "smaller is weaker" nor "smaller is stronger" behavior is controlling the macroscopic yield [9]. The details of the mechanical tests are given in [10] and the main results are simply recalled here. Uniaxial tension is performed on dog-bone specimen, with a width of 12.5 mm and a gauge area of 57 mm, whereas rectangular samples of gauge area 30 mm × 3 mm are used for simple shear, together with a specific anti-buckling device [7].

For both tests, the strain is calculated as an average over an area of interest using Digital Image Correlation and Cauchy stress is calculated from the load. Stress-strain curves in tension are displayed in Fig. 1(a). It can be seen that pure Cu exhibits a yield stress of 186 MPa, much lower than the yield stresses of CuBe2 and CuFe2P, respectively 385 MPa and 335 MPa. Moreover, CuFe2P alloy exhibits a rather low strain hardening, whereas it is higher for both pure Cu and CuBe2. Indeed, using the ratio of the difference between the ultimate tensile stress $R_m$ and the conventional yield stress $R_{p0.2}$ over the initial yield stress as a measure of the work hardening, it comes similar ratios of 36% and 34.5% for pure Cu and CuBe2 alloys but a lower one, 25%, for CuFe2P. Plastic anisotropy coefficients are also measured and normal anisotropy coefficient $\bar{r}$ and planar anisotropy variation $\Delta r$ are given in table 1, as well as Young’s modulus.

![Stress-strain curves](image)

**Figure 1.** Stress-strain curves for the three materials.

The unloading slope in tension evolves significantly with plastic strain. For CuFe2P, it decreases from 114 GPa down to 94 GPa, that corresponds to a relative decrease of 17% of the initial value, over a rather limited strain range of 0.04, whereas the evolution for CuBe2 is gentler, with a decrease from 126 GPa down to 85 GPa (relative gap of 33%) over a strain range of 0.13.
Table 1. Mechanical properties measured in tension for the three materials.

|       | E (GPa) | $R_{p0.2\%}$ (MPa) | $R_m$ (MPa) | $\bar{r}$ | $\Delta r$ |
|-------|---------|---------------------|-------------|-----------|------------|
| Cu 99.9% | 104     | 186                 | 253         | 0.69      | 0.08       |
| CuFe2P  | 114     | 335                 | 419         | 0.60      | 0.15       |
| CuBe2   | 126     | 385                 | 518         | 0.92      | 0.28       |

Stress-strain curves in simple shear are displayed in Fig. 1(b). Monotonic tests are performed, as well as tests composed of loading up to several strains, then unloading and reloading in the reverse direction. To quantify the magnitude of Bauschinger’s effect, the reverse reloading is plotted positively. The three materials exhibit a typical rounded re-yielding point and a transient lower yield stress upon reloading for pure Cu and CuBe2.

Mechanical properties, i.e. Young’s modulus, initial yield stress, hardening rate, magnitude of the Bauschinger effect and evolution of the unloading slope can significantly influence springback. For example, a larger initial yield stress over Young’s modulus ratio leads to a larger springback. The three alloys presented here exhibit some differences, in particular regarding the stress level, the hardening rate and the permanent softening after stress reversal.

3. Experimental investigation of springback
Rectangular sample of dimensions 100 mm × 28 mm are cut with the largest dimension parallel to the rolling direction. Samples oriented along the transverse direction are also tested; however, the influence of anisotropy on twisting is rather weak and is not further investigated in this article.

A dedicated rig, which dimensions are shown in Fig. 2(a), is used for the forming of a U-shaped elongated part. A punch stroke of 7 mm is used for all samples and after drawing, tools are removed. To enhance twisting, a controlled misalignment of the rectangular blank with respect to the tools is imposed equal to 2°. This misalignment leads to non-symmetric parts with respect to the direction parallel to the part length, with short and long flanges at the two extremities; however, the middle section is symmetric.

![Figure 2. 2D schematic drawing of the rig used for springback investigation (a) and final geometry of a pure copper part after tool removal (b).](image-url)
The final geometry of the drawn parts (Fig. 2(b)) is measured using a laser scanner fixed on a 3D measuring machine; a data-point cloud is created and post-treated, to extract the coordinates of points lying on several sections taken along the specimen length. The twisting parameter is calculated as the ratio of the relative angle $\alpha$ between the two end section bottoms over the distance in-between the sections (Fig. 3): the two end sections are output from the data-point cloud and a linear interpolation is performed. The relative angle between these two lines is calculated. Fig. 4(a) shows the shape after forming and springback for the three materials. Fig. 4(b) shows that a good reproducibility is obtained, as evidenced over four different tests for each material. An average value of the twisting parameter is calculated, leading to respectively $28^\circ \text{m}^{-1}$, $8^\circ \text{m}^{-1}$ and $45^\circ \text{m}^{-1}$ for pure Cu, CuBe2 and CuFe2P.

![Figure 3. Definition of the twisting parameter.](image)

![Figure 4. Superimposition of the final shapes after drawing and springback (a) and reproducibility of the twisting parameter (b) for the three materials.](image)

4. Discussion

A huge influence of the material on springback is evidenced (Fig. 4(a)). In order to further understand these differences, 2D springback of each section is analysed. It is classically quantified by three parameters: (i) the angle $\theta_1$ that estimates the opening between the bottom of the section and the wall, (ii) the angle $\theta_2$ representing the opening between the wall and the flange, and (iii) the curvature radius of the wall $\rho$ [3]. These parameters are calculated from
the 2D profiles via a dedicated program developed within Scilab environnement. The evolution of these parameters for three sections, in the middle of the length and at the two extremities, and the different tests is plotted, as well as the average values. Globally, though there are some variations, in particular for the wall curvature radius of CuFe2P samples, trends are clearly observed.

For pure Cu (Fig. 5), $\theta_1$ is of the order of 100°, $\theta_2$ of 85° whereas $\rho$ has a low value for the long and middle flange sides (20 mm) and a large one for the short flange sides (70 mm).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5}
\caption{Evolution of the 2D section parameters for pure Cu.}
\end{figure}

CuBe2 exhibits a large opening compared to the other two materials, characterised by a very low value of the wall curvature, with $\rho$ around 8 mm and independent of the flange size (Fig. 6). The average values for $\theta_1$ and $\theta_2$ are respectively 120° and 76°.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6}
\caption{Evolution of the 2D section parameters for CuBe2.}
\end{figure}

Similar shapes for Cu and CuFe2P are observed, with a nearly straight wall for small flange ($\rho = 80$ mm) and a lower value of 20 mm for long and middle flange sizes (Fig. 7). The two angles $\theta_1$ and $\theta_2$ have values very close to the ones calculated for pure Cu, i.e. respectively 105° and 85°.

There is therefore a close relationship between the twisting parameter and the 2D springback. Indeed, CuBe2 samples exhibit a large opening of the section, whatever the flange side, which corresponds to a low twisting parameter of $8^\circ \text{m}^{-1}$. Out of comparison’s sake, a twisting parameter below $5^\circ \text{m}^{-1}$ is recorded for samples perfectly aligned with the tools, for stainless steel [3] and also pure Cu sheets. Pure Cu and CuFe2P samples exhibit more twisting and less opening of the 2D sections. The trend is all the more higher than the yield stress is higher. The main difference between CuBe2 and CuFe2P alloys mechanical behavior is a higher hardening rate for CuBe2 than for CuFe2P. Finally, with the same device, similar thickness and the same misalignment, an average twisting parameter of $11^\circ \text{m}^{-1}$ is calculated for stainless steel.
Figure 7. Evolution of the 2D section parameters for CuFe2P.

sheets [3,6]. These results constitute an interesting experimental database to validate numerical predictions of the springback step, as performed for stainless steel [6].

5. Conclusions

Three materials provided as ultra-thin sheets (thickness around 0.1 mm), pure Cu and two Cu alloys, are considered in this study. Their mechanical behavior in uniaxial tension and simple shear is compared: CuBe2 and CuFe2P have similar initial yield stresses, much higher than pure Cu. However, CuFe2P exhibits a low strain hardening rate compared to the other two materials, as well as almost no transient softening in the case of Bauschinger type simple shear tests, though the rounded yield point is similar for the three materials. Deep drawing of elongated (100 mm) U-shaped channels, misaligned by 2° with respect to the forming tools, is performed and the shape after springback is measured; reproducibility is checked over four different samples and global trends are clearly observed, highlighting the influence of the material on springback. CuBe2 samples show a negligible twisting parameter of 8° m⁻¹ whereas a large opening of the 2D section is observed, with a large θ₁ angle. On the contrary, CuFe2P samples are characterised by a very large twisting parameter of 45° m⁻¹ but a small variation of the 2D section.

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