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An Experimental Investigation of the Size Effects in Forming Processes of High-Purity Thin Metallic Sheets

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Abstract. Miniaturization of small metallic systems can lead to a softening of the mechanical behavior due to the reduction of scale. Size effects have been considerably studied recently for materials with various crystallographic structures. Under tensile conditions, thin specimen exhibit softer mechanical properties when the number of grains across thickness is lower than a critical number and this modification appears above a critical strain level. In this work, stamping tests were performed on five hundred micrometers in thickness sheets of hexagonal closed-packed cobalt. The results are compared with those obtained for face centered cubic copper and nickel. The influence of thickness over grain size ratio was studied for several proportional loadings linked to forming processes. Complex loadings were applied with 20 mm hemispherical punch and strain paths were checked with a 3D video extensometer. Hill criterion was systematically used to take into account the anisotropy of the samples. Our results revealed that the critical strain level for which the size effects appears is strongly sensitive to the stress triaxiality which, in turn, is closely dependent to the loading path.

Introduction

In recent years, the size of industrial parts has been continuously decreased and the demand of several industrial domains such as electronic, medical, automotive, aeronautics... has continued to grow [1-4]. Nowadays it is not possible to produce parts with smaller dimensions without taking into account the size effects. Due to these effects, the mechanical behavior is strongly affected when the scales are reduced. Several previous studies reported a softening of the stress when the number of grains across the thickness, characterized by the ratio between the thickness (t) and the grain size (d), is reduced. This softening takes place when t/d becomes lower than a critical value $(t/d)_c$ and for a critical strain level ε_c . A sample is defined as multicrystalline when its number of grains across the thickness is lower than $(t/d)_c$. Concerning the microstructure, the stress softening is due to the establishment of surface effects. These surface effects are characterized by an internal stress gradient across the thickness due to a delay of the activation of the strain hardening stages in the surface grains.

Generally, size effects are studied in tension for materials with well-known deformation mechanisms such as face centered cubic materials [5-9]. A recent study on hexagonal close-packed cobalt evidenced a stress reduction when t/d is lower than 14 which appears from the elastic domain [10]. Both critical parameters $(t/d)_c$ and ε_c can be directly estimated using the stacking fault energy γ_{SFE} of the materials [8, 11]. A few studies have shown that these critical parameters may be temperature sensitive [9, 12, 13] and/or stress triaxiality sensitive [14-16].

The aim of this work is to perform experimental investigation concerning the influence of the stress triaxiality on the transition between polycrystalline and multicrystalline behaviors. To this end, different loadings close to forming processes were performed. Various geometries of sample are stamped with a hemispherical punch to produce controlled stress triaxiality. The chosen material is high purity cobalt (hexagonal close-packed - HCP - structure with $\gamma_{SFE}(Co) = 27 \text{ mJ.m}^{-2}$) and is compared with previous results obtained for copper and nickel (face centered cubic - FCC - structures with respectively $\gamma_{SFE}(Cu) = 45 \text{ mJ.m}^{-2}$ and $\gamma_{SFE}(Ni) = 125 \text{ mJ.m}^{-2}$). Material properties

and experimental procedures are given in the next section. Experimental results are therefore presented in the third section, highlighting the force softening when the number of grains across the thickness is reduced, for the different loading conditions and the three materials. The critical parameters are determined and the influence of the stress triaxiality on them is studied. Finally, the optimal conditions for the forming of thin sheets could be conveniently depicted thanks to original deformation plots taking into account the size effects.

Material features and experimental procedure

High purity polycrystalline cobalt (> 99.99wt. %) consisting of 0.5 mm thickness rolled sheets were annealed in secondary vacuum in order to obtain various t/d ratio without oxide layers. The temperature was fixed at 1373 K during various time durations in the range [1-96] hours. For each sample, Electron BackScattered Diffraction (EBSD) analysis was performed to obtain the grain size, the crystallographic texture and the proportion of the FCC retained phase for cobalt. The values of t/d ratio range from 4.5 to 34. For all cobalt samples, a strong basal (0001) texture in the sheet plane, representative of a HCP laminated state [17] is revealed, while copper and nickel samples do not present specific texture. The proportion of the retained FCC phase in the HCP phase is about 10 % for all cobalt samples, in accordance to Zhu et al. [18].

For each sample, the Lankford coefficient r was evaluated. Tensile tests were carried out on dog bone shaped samples with a gauge section of 25 mm in length and 10 mm in width. A stochastic pattern was sprayed on the sample surface. Strain measurements were achieved by digital image correlation (DIC) on captured, by a CCD high resolution camera, images. Two virtual extensometers were placed on the length and on the width of samples. Assuming plastic incompressibility, we obtain the ratio between minor plastic deformation ε_{II} (deformation in the width direction) and the deformation in the thickness ε_{III} . This ratio is the expression of the Lankford coefficient.

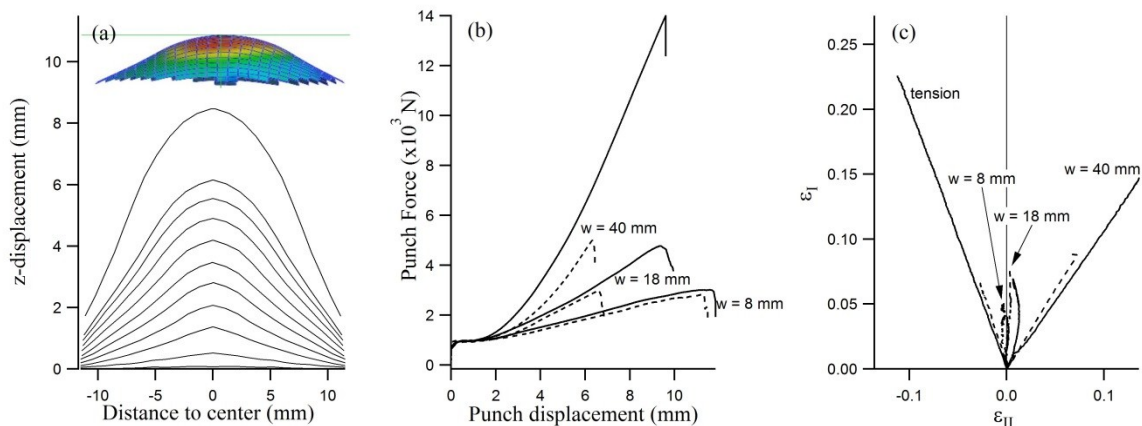


Fig. 1. Typical evolution of the z-displacement of a plain circular blank during a punch experiment (a). Force-displacement curves (b) and corresponding strain paths (c) for two cobalt samples: $t/d = 34$ (full line) and $t/d = 6.8$ (dotted line).

Three blank geometries were chosen to have different strain paths: a circular blank with $w = 40$ mm radius and two notched blanks with a constant width of $w = 18$ mm and $w = 8$ mm. Stamping tests were performed with a 20 mm hemispherical punch. The large ratio between the punch radius and the blank thickness (0.5 mm) allows to assume plane stress deformations ($\sigma_{III} = 0$). A large description of the experimental procedure is provided in [14]. During stamping tests, strain measurements were achieved by two cameras for 3D DIC. The plain circular blank gives a balanced biaxial expansion, the notched blank with $w = 18$ mm have a plane strain loading and $w = 8$ mm permits to obtain a negative ratio $\beta = \varepsilon_{II}/\varepsilon_I$. Fig. 1 (a) represents the displacement of a circular blank along the z-axis during the punch rise. The punch force is plotted versus the punch displacement for two t/d values, for the three complex loadings, in Fig. 1 (b). A gap can be observed between curves for the different t/d . The applied force is more important for the blank with higher widths. Fig. 1 (c)

shows the experimental strain paths for both t/d ratios. The normal plastic anisotropy affects yield criterion, in accordance with Hill's works [19, 20]. Assuming the normality of the plastic flow, the strain path is also modified by the number of grains across the thickness.

Experimental results and discussion

Mechanical behavior modification. To emphasize the force gap between the different t/d ratio revealed on Fig. 1 (b), the punch force is plotted for each number of grains across thickness and for several equivalent deformation, in Fig. 2 for balanced biaxial expansion, plane strain loading and for blank with a 8 mm width. Whatever the loading path, the punch force is softened when the number of grains becomes lower than the same critical value of 14 determined previously in tension [10]. This softening appears for a critical strain level ε_c , which seems strain path dependent. The modification of the behavior is observed from $\varepsilon_c = 0.11$ when biaxial expansion conditions are applied. Concerning the plane strain loading, the multicrystalline stage occurs for $\varepsilon_c = 0.04$ and for $\varepsilon_c = 0.015$ in the case of the blank of 8 mm width. When strain levels are lower than ε_c , punch force increases linearly with t/d ratio and can be similar to a Hall-Petch type law.

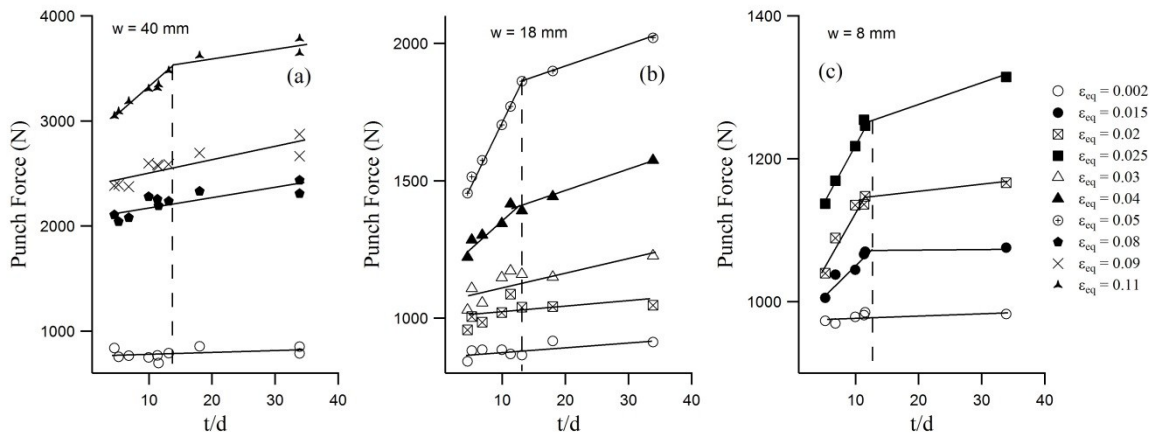


Fig. 2. Punch force vs. t/d ratio for various strain levels for plane circular blank (a), notched blank with 18 mm width (b) and notched blank with 8 mm width (c). Cobalt specimens.

Normal plastic anisotropy and thickness reduction measurements. The Lankford coefficient has the same value in all the directions of the sheet plane but is always lower than the unity. Each material then presents a normal plastic anisotropy and has a preferential deformation in the thickness. The Hill's criterion has to be used to calculate the equivalent plastic strains and the equivalent plastic stresses. Fig. 3 shows the evolution of the Lankford coefficient with the t/d ratio. The three metals become strongly anisotropic as t/d decreases. They will progressively deform through the thickness in accordance with the literature [21]. It is interesting to note that the Lankford coefficient has the same sensitivity to t/d for copper and cobalt. r is closely linked to the stacking fault energy, independently on the material.

The thickness deformation ε_{III} can be evaluated throughout the test assuming the plastic incompressibility. Knowing the major and the minor deformations and applying this principle, ε_{III} can be calculated and the thickness reduction is determined. The maximum thickness reduction presented in Fig. 3 for cobalt is located on the top of the dome and was measured just before fracture occurs. This thickness reduction is plotted versus the number of grains across the thickness for each complex loading. A sensitive reduction of thickness is expected for low t/d . The material exhibits a strong normal plastic anisotropy (with $r < 1$) for low t/d and deforms more sharply in thickness. Furthermore, the thickness reduction is more pronounced for loadings with high stress triaxiality. The maximal thickness reduction is reduced with the number of grains across thickness and in a more rough way for the balanced biaxial loading.

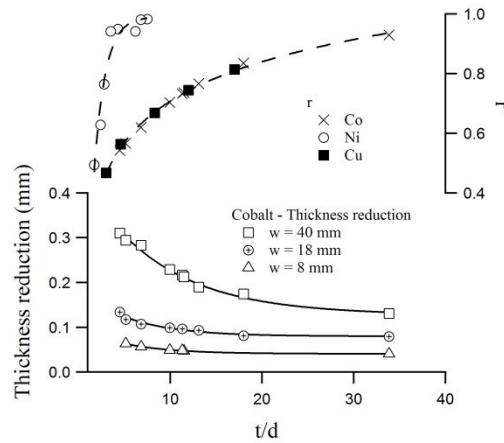


Fig. 3. Influence of the t/d ratio on the normal plastic anisotropy r (dotted line) for copper, nickel [14] and cobalt and on the maximum of the thickness reduction during stamping tests (full line) for cobalt.

Discussion. Assuming plane stress deformation, proportional loading and using the Hill flow rule for pure normal plastic anisotropy, the stress triaxiality η can be expressed in function of the principal deformation ε_I and ε_{II} by Eq.1 [22]:

$$\eta = \frac{1 + \frac{2\varepsilon_{II} + \varepsilon_I}{2\varepsilon_I + \varepsilon_{II}}}{3 \sqrt{1 + \left(\frac{2\varepsilon_{II} + \varepsilon_I}{2\varepsilon_I + \varepsilon_{II}}\right)^2 - \frac{2r}{1+r} \frac{2\varepsilon_{II} + \varepsilon_I}{2\varepsilon_I + \varepsilon_{II}}}} \quad (1)$$

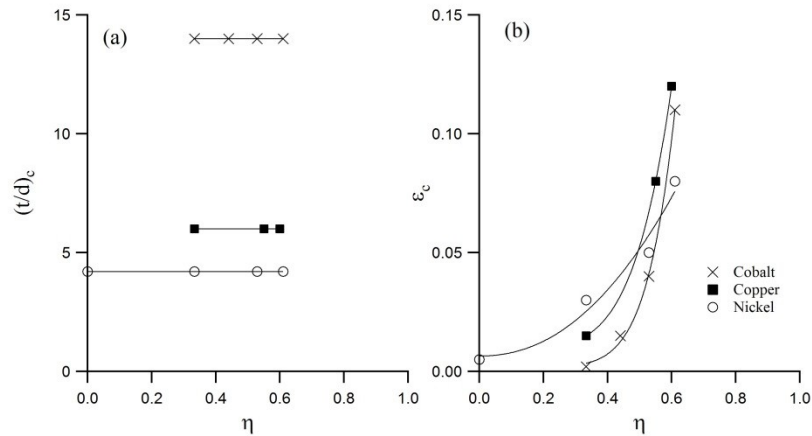


Fig. 4. Evolution of the critical number of grains across the thickness (a) and the critical strain level (b) with the stress triaxiality for cobalt (crosses), copper (plain squares) and nickel (open circles).

Fig. 5 (a) is the representation of the forming limit curve for polycrystalline cobalt samples and for multicrystalline cobalt. The most critical loading is obtained for a geometry of blank of 8 mm width. This geometry is also the only one which seems independent from the size of the microstructure. Fig. 5 (b) is a map which indicates, according to the strain level induced by the forming process, if it is necessary to expect to have a softening of the properties with regard to a bulk material. For $t/d > (t/d)_c$ and whatever the strain level, polycrystalline cobalt behaves like a massive one. For $t/d < (t/d)_c$, this behavior is representative, if the deformation generated by the process is located in the light grey region. When $t/d < (t/d)_c$ and $\varepsilon > \varepsilon_c$ (in the light red region), it is necessary to take into account the force reduction due to the size effects depicted in Fig. 2.

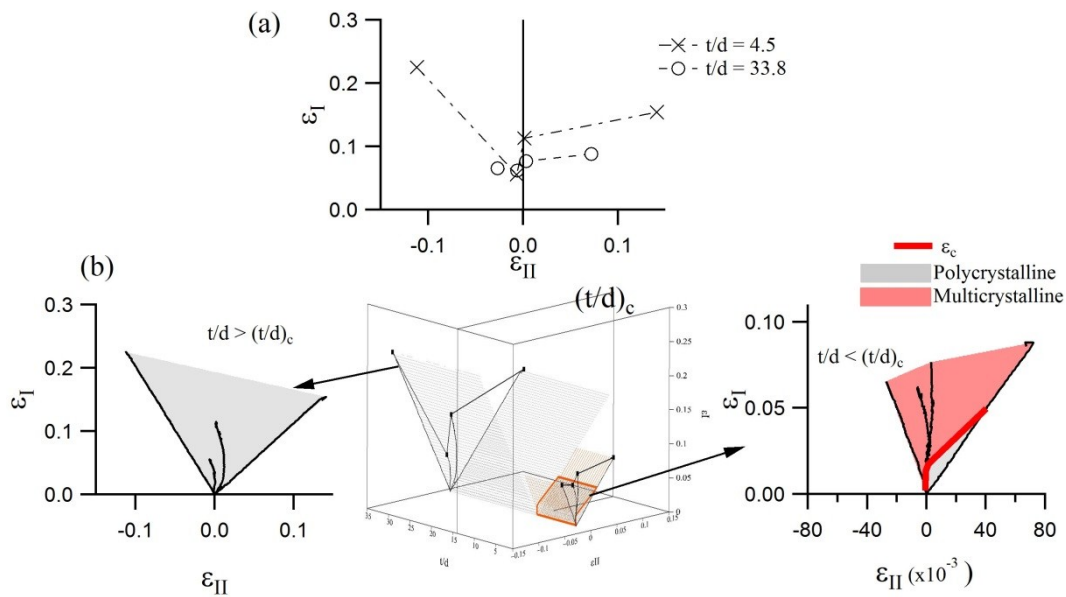


Fig. 5. Forming limit curves for two t/d ratios, $t/d = 4.5$ and $t/d = 33.8$ (a). Size effects maps showing optimal forming conditions when $t/d > (t/d)_c$ (left) and when $t/d < (t/d)_c$ (right) (b).

Conclusion

In conclusion, this experimental study concerning size effects during forming for high-purity copper, nickel and cobalt leads to the two main following results:

- Independently to the loading paths, mechanical properties of thin sheets are softened when the number of grains across the thickness becomes lower than a critical value which is dependent on stacking fault energy.
- High stress triaxiality tests compared to the tensile conditions revealed that the behavior degradation is more and more delayed toward the higher deformation levels when the stress triaxiality is increased.

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