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AUTHOR(S): S. S. Hecker
Materials Science and Technology Division
Los Alamos National Laboratory
Los Alamos, NM 87544

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FACTORS AFFECTING PLASTIC INSTABILITY AND SHEET FORMABILITY

Siegfried S. Hecker

Materials Science and Technology Division
Los Alamos National Laboratory
Los Alamos, NM 87545
U.S.A.

ABSTRACT

The strong influence of geometry and materials properties on plastic instability and sheet formability is illustrated with several experimental observations. Geometry (shape) of the specimen or work piece and the evolution of shape with deformation is of great importance. Experiments on sheet and thin-walled tubes have demonstrated convincingly that sheets stretched over a punch are more stable than sheets stretched in-plane; which, in turn, are more stable than expanded thin-walled tubes. All can be explained by the specific interaction of specimen shape with loads and deformations. The materials parameters of greatest importance (Hecker, 1978a) are strain hardening, strain-rate sensitivity, and plastic anisotropy. Several experiments are cited that demonstrate the importance of stress state, large strains, and path changes on the strain-hardening response and on subsequent stability.

KEYWORDS

Plastic instability, sheet metal forming, strain hardening, punch stretching, multiaxial stresses, large strains.

INTRODUCTION

The prediction of the onset and development of plastic instability is a most difficult and important problem. It requires the proper treatment of large geometrical changes and an accurate description of strain hardening at large strains and under changing deformation paths. The problem of plastic instability in thin sheets and its relation to sheet formability has received much recent attention (see the proceedings edited by Hecker, Gosh and Gegel, 1978; Koistinen and Wang, 1978). The important role of geometry and materials properties on plastic instability is being recognized. In this paper, some of the unusual experimental observations in the sheet forming literature will be reviewed and explained on the basis of the effects of geometry and material properties on instability.

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THE INFLUENCE OF GEOMETRY

Ghosh and Hecker (1975) demonstrated that the increased useful deformation (as defined by a forming limit curve) observed in punch (out-of-plane) stretching compared to in-plane stretching of sheet results from differences in deformation geometry. Figure 1a illustrates the different test techniques used by Hecker (1978a) for the results on commercially pure

Fig. 1a. Schematic diagrams of punch apparatuses used for in-plane and punch-stretch experiments

annealed aluminum (Fig. 1b). For in-plane stretching, deformation is uniform and local necking should not occur in biaxial tension unless local inhomogeneities are admitted (Marciniak and Kuczynski, 1967; Marciniak, Kuczynski, and Pokora, 1973) or constitutive descriptions other than J_2 flow theory are used (Stören and Rice, 1975; Hutchinson and Neale, 1973; Tvergaard, 1978). Specifically, it has been demonstrated that deformation

Fig. 1b. Forming limit curves for 1100 aluminum. A comparison of in-plane and punch stretching.

(in contrast to flow) theories of plasticity predict localized making in biaxial stretching at reasonable stress levels. Bifurcation analyses by Stören and Rice (1975) using J_2 deformation theory with a yield locus vertex and by Tvergaard (1978) using kinematic hardening and small initial inhomogeneities predict realistic critical strain levels at instability. In punch stretching, no restriction to local instability exists because a strain gradient develops immediately upon punch to sheet contact. In spite of this strain gradient, stability during punch stretching is prolonged because the geometry of the ever-expanding cup delays the attainment of localized plane strain required for local necking.

The geometry differences can also cause a significantly different sensitivity to some materials properties. In punch stretching, the deformation is always nonuniform and the location of the neck is, in large part, dictated by geometry. Hence, second-phase inclusions or particles that may trigger early fracture are detrimental only if they exist in the narrow band where necking eventually occurs. For in-plane stretching, the entire sheet is stretched uniformly and, hence, inclusions in any portion of the sheet may trigger early fracture. Therefore, the in-plane techniques show a much greater sensitivity to imperfections (including material cleanliness) than punch stretching techniques or what is normally found in metal stampings.

The profound influence of geometry on plastic instability was even more convincingly demonstrated by Stout and Hecker (1983) in the comparison of sheet to thin-walled tubes. The onset of diffuse instability (maximum uniform deformation) was found to be very sensitive to geometry as demonstrated in Fig. 2. In biaxial, combined tension-internal pressure experiments, we found that the uniform strain in tubes for axial plane strain

• EXPERIMENTS ON TUBES

Fig. 2. A comparison diffuse instability strains for the 70-30 brass tubes and sheet. ϵ_1 and ϵ_2 refer to major and minor time strains, respectively

(no length change) is twice that for hoop plane strain (no diameter change). In the comparison of tubes and sheet, we found that the uniform strain in balanced biaxial tension in tubes is only one-third of that in sheet. The strain levels for local necking and fracture were similar for tubes and sheet (no geometry effect). However, the useful deformation beyond diffuse instability for tubes is very limited because localization occurs rapidly. In punch-stretched sheet the geometry is stable and localization occurs gradually, providing substantial post-uniform deformation.

PLANE STRAIN BEHAVIOR

The resistance to plastic instability during stretching of α -brass is considerably less than what one expects on the basis of its uniaxial tensile behavior (Ghosh, 1978; Wagoner, 1982). This is particularly true for plane-strain deformation. It is well recognized that brass typically exhibits zero strain rate sensitivity and, hence, unlike low-carbon steels, its stability does not benefit from a contribution of positive strain rate sensitivity (Hecker, 1978a). Ghosh (1978) and Wagoner (1982) explained the brass instability behavior on the basis of a stress-state dependence of work hardening. A limited number of experiments in plane-strain tension suggested a lower work hardening rate than in uniaxial tension. Hecker and Stout (1983) performed extensive stress-state tests on α -brass tubes and also found a definite stress state effect. As observed by Ghosh and Wagoner, plane-strain hardening is low; however, balanced biaxial hardening is similar to that in uniaxial tension (see Fig. 3).

Fig. 3. Comparison of stress-strain curves for 70-30 brass thin-walled tubes (Hecker and Stout, 1983). Curve #2 represents the results for three different stress states; torsion, plane strain with no length change ($\epsilon_z = 0$), and plane strain with no diameter change ($\epsilon_\theta = 0$). Curve #1 represents uniaxial hoop tension.

The thin-walled tube tests on brass are limited to strains <0.4 because of the onset of plastic instability. As mentioned above, sheets are able to sustain larger useful deformation and, hence, it would be beneficial to assess strain hardening at larger strains. This is a most difficult task because of the large geometric changes that occur and the tendency for instabilities and other deformation inhomogeneities. Hecker and Stout (1983) compared the strain hardening in axisymmetric compression to torsion at strains up to 3.0. The results shown in Fig. 4 clearly demonstrate the lower work hardening rate (when compared on the basis of a von Mises criterion) in plane strain torsion compared to axisymmetric compression. The hardening response in tension up to instability is similar to that in compression. Hecker and Stout demonstrated that in brass most of the difference in hardening can be explained on the basis of textural evolution. A review of several other materials including other modes of deformation indicates that the lower hardening in plane strain deformation modes appears to be quite common (Hecker and Stout, 1983). The implications of this observation to sheet forming is obviously of great importance.

Fig. 4. Comparison of stress-strain curves for 70-30 brass for uniaxial tension, compression and torsion (Hecker and Stout, 1983). Tension and torsion were carried out on identical thin walled tubes. Compression was carried out on solid rod, remachined often to avoid barreling.

We should point out that the most thorough study comparing torsion and axisymmetric deformation was carried out by Jonas and co-workers. (1982) on copper. In conjunction with a new theoretical development on texture evolution (Canova, Kocks, Jonas, 1982), they found that texture explained approximately half of the hardening difference. The rest must be a result of differences in slip behavior for different stress states.

LARGE STRAIN BEHAVIOR

Comparison of forming limit curves of low-carbon steels with aluminum alloys shows that steels are much more resistant to local plastic instability (Hecker, 1978a). Much of this difference can be attributed to the positive strain rate sensitivity of steel compared to either the zero or negative sensitivity of many aluminum alloys. However, another important factor is the strain hardening at large plastic strains, beyond those typically attained in uniaxial tensile tests. These strain levels are important because in punch stretching (or in many metal stamping operations) much useful deformation can be obtained beyond the maximum uniform strain in tension. However, it is extremely difficult to measure strain hardening accurately at large strains. Hecker and Stout (1983) have measured strain hardening at large strains for a few materials using compression, torsion, and rolling followed by tension. From their work and a review of the literature they concluded that hardening persists at large strain for most materials. Several factors, however, favor a saturation in hardening. The most prominent are plane strain deformation modes and high purity (low solute content). Also, other microstructural features may favor inhomogeneities such as shear banding and also result in saturation.

The importance of strain hardening at large strains was demonstrated by Bird and Duncan (1981). They compared the forming limit curves (FLC) of 1008 steel, 1100 (commercially-pure) Al and 2036-T4 Al (the experimental curves as determined by Hecker (1978a) are shown in Fig. 5). The strain hardening

Fig. 5. Forming limit curves of three materials from Hecker (1978a, 1978b).

exponents (n-values from $\sigma = K\varepsilon^n$, where σ is the flow stress, ε the plastic strain, and K a strength constant) in uniaxial tension were between 0.21 and 0.26 for all three materials. The low FLC for 2036-T4 Al was explained by Hecker on the basis of its negative strain rate sensitivity (m-value from $\sigma = k'\varepsilon^m$ of -0.005). However, steel has a positive m value of 0.012, whereas 1100 Al is rate insensitive, which suggests that the FLC for steel should be higher. Bird and Duncan (1981) showed that strain hardening at

large strains provides the explanation. Figure 6 shows the strain hardening data derived by Bird and Duncan from hydraulic bulge tests on sheet.

Strain hardening is represented by the normalized hardening slope, $\frac{1}{\sigma} \frac{d\sigma}{d\epsilon}$.

In uniaxial tension the maximum uniform strain attainable occurs when

$\frac{1}{\sigma} \frac{d\sigma}{d\epsilon} \approx 1$. At strains up to this level the hardening rates are similar.

However, at larger strains the hardening rates begin to differ dramatically. The high hardening rate of 1100 Al apparently offsets the zero strain rate sensitivity when comparing the FLCs for 1100 Al and steel. Hardening for 2036-T4 Al is the lowest, contributing further to its poor FLC behavior.

Fig. 6. Hardening rate normalized by stress as a function of strain for hydraulic bulge tests from Bird and Duncan (1981).

STRAIN PATH CHANGES

The importance of strain path changes on plastic instability and the forming limit curve have been discussed by several authors (Ghosh and Laukonis, 1976; Kleemola and Pelkkikangas, 1979). The effect on stability arises from transients in hardening and geometrical considerations. Most path changes result in some softening (and hence destabilizing) transients because of the generalized Bauschinger effect. Hardening or softening beyond the initial transient depends on the stress state influence. For instance, a change in path towards plane strain from axisymmetric deformation will most likely result in a decreased strain hardening rate (Kocks, 1983).

The combined effect of hardening transients and geometry can be illustrated very effectively by examining the ductility or (formability) of heavily cold worked metals. Hecker (1978b) demonstrated the effects of prior cold work (by rolling) on the FLCs of 1100 aluminum. The results (Fig. 7) show that increasing prior cold work drastically reduces subsequent uniaxial and plane-strain ductility, with little effect on balanced biaxial ductility.

Fig. 7. Failure limit curves of 1100 aluminum for annealed and cold-rolled conditions. Failure is defined by local necking. Sheet thickness is 0.635 mm (Hecker, 1978b).

periments by Hecker and Stout (1983) established the large-strain hardening response of 1100 aluminum. The stress-strain curve determined from rolling followed by tension experiments exhibits continued hardening to very large strains. In Fig. 8 we see that after a prestrain of 90 percent ($\epsilon = 2.3$),

Fig. 8. Stress-strain curve and hardening rate (θ) for 1100 aluminum (Hecker and Stout, 1983). Dashed curve labelled T represents uniaxial tension on annealed material. The curve at true thickness strain of 2.3 represents tension following a prestrain of 2.3.

aluminum is still quite capable of hardening. However, after a prestrain of 90 percent a specimen pulled in uniaxial tension becomes unstable almost immediately as shown in Fig. 8. The lack of stability in tension is easily understood. For rate-insensitive material, tensile instability occurs when $d\sigma/d\varepsilon = \sigma$. Figure 8 shows the curve for σ and $d\sigma/d\varepsilon$ as a function of strain. They cross at a point where tensile instability is observed in an annealed specimen ($\varepsilon \approx 0.25$). During rolling the flow stress is increased much beyond the ultimate strength in uniaxial tension. However, the intrinsic hardening rate ($d\sigma/d\varepsilon$) decreases. For the prestrain of 2.3 chosen in Fig. 8, the flow stress is obviously much greater than the level that could be supported by the intrinsic hardening rate. Therefore, the tensile specimen should go unstable immediately upon yielding. In actuality, some stability is observed because of the generalized Bauschinger effect. Yielding occurs before the prestrain stress level is reached and the hardening rate is temporarily increased to help support the stress level. As demonstrated in Fig. 9, this effect is transient and leads to limited ductility.

Fig. 9. Enlargement of Fig. 8 near the prestrain level of 2.3. Subscript R refers to rolling curve and t to subsequent tension. The solid σ_t curve represents the engineering stress-strain curve. True stress-strain behavior is labelled True σ .

In biaxial stretching, particularly in punch stretching, deformation is much more stable geometrically and, hence, the material is able to take better advantage of its intrinsic hardening and exhibit much greater ductility (see Fig. 7).

In summary, the importance of geometry and strain hardening (especially the influence of stress state, strain and path changes) on plastic instability have been demonstrated with the aid of several experimental observations on sheet and thin-walled tubes.

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