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PLASTIC FLOW PARAMETERS OF BRASS SHEETS UNDER UNIAXIAL AND BIAXIAL TENSILE TESTING

The value of the strain hardening exponent (n) and plastic anisotropy ratio (r) of two kinds of brass sheets were determined in uniaxial tensile and equibiaxial stretching tests. It was established that especially the value of n-parameter of brass sheets strongly depends on the specimen deformation and stress/strain state. The effect of instantaneous (differential) n_t-value and r_t-value on the forming limit curve was obtained.

Introduction

Formability of sheet metal is dependent on the mechanical properties of the metal. Some materials form better than others. Moreover, a material that has the best formability for one stamping may behave very poorly in a stamping of another configuration. For these reasons, extensive test programs are often carried out in an attempt to correlate material formability with value of some mechanical properties. The formability of sheet metal has frequently been expressed by the value of:

- strain hardening exponent n,
- and plastic anisotropy ratio r.

The stress-strain and hardening behaviour of a material is very important in determining its resistance to plastic instability. In sheet forming operation biaxial as well as uniaxial stress state exist. Thus, one must known and understand material hardening behaviour as a function of stress state [1÷4]. Additionally the value of the n and r parameters depend on the grain size of the material [5] and changes as plastic deformation accumulates.

Since experimental determination of the forming limit diagram of a sheet metal is very time- and material-consuming, the knowledge of the above mentioned relations could be very useful in the theoretical calculations of the limit strains of a sheet under different strain state. We might to expect that calculations of the forming limit diagram using instantaneous (elongation dependent, differential) value of the normal anisotropy ratio r_t and strain hardening exponent n_t enable to achieve better correlation between calculated and experimental results.

Experimental studies of formability of various materials have, however, revealed basic differences in behavior, such as the "brass-type" and the "steel-type" [6], exhibiting respectively, zero and positive dependencies on forming limit upon the strain ratio. Such results cannot be reconciled without proper attention to the details of strain hardening behaviors of these materials, particularly as functions of strain and strain ratio.

Modern universal testing machines with appropriate measuring systems for length-width variations allow the usual characteristic values to be ascertained together with *r* and *n* values, both rationally and with a high accuracy.

Material and mechanical testing

The tests were carried out on the 1.0 mm thick 80-20 and 0.5 mm thick 63-37 brass sheets in annealed state. The tensile specimens of 50 mm gauge length and 12.5 mm width, were prepared from strips cut at 0, 45 and 90° according to the rolling direction of the sheet. The experiments were carried out using a special device which recorded simultaneously the tensile load, the current length and width of specimen, using a microcomputer.

In order to determine the flow properties of a material in biaxial stretching, the bulge test was carried out, using hydraulic bulge apparatus with a circular die aperture of 100 mm diameter. The bulging pressure and the curvature of the pole were measured and recorded continuously up to specimen failure.

Plastic anisotropy ratio

Normal anisotropy value represents the ratio of the natural width deformation in relation to the thickness deformation of a strip specimen elongated by uniaxial tensile stress:

$$r = \frac{\varepsilon_w}{\varepsilon_t} \tag{1}$$

The r-value at a given elongation, usually 15 pct (effective strain $\varepsilon = 0.14$) has been used for many years as a quality control indicator of drawability. More recently, there has been interest in the effect of strain on the plastic ratio, while acknowledging that the changes in the crystallographic texture occurred with increasing strain. For plasticity studies, the basic definition of r-value has been replaced with the instantaneous r_t-value, which is defined as:

$$r_t = \frac{d\varepsilon_w}{d\varepsilon_t} \tag{2}$$

According to some experimental results [1, 5] no systematic increase or decrease of r_t-value with strain was observed, in contrast to previous reports in the literature. The test results for different materials and for different specimen orientation (Fig. 1) have shown that in the case of the 80-20 and 63-37 brass sheets no clear correlation between plastic anisotropy ratio and specimen elongation exists. And because of that the r-value of brass sheet was determined using [7] method (Fig. 2), and it could be treated as a reasonable representation of anisotropic behaviour over a wide range of elongation.

Strain hardening exponent

For many years strain hardening laws such as those from Ludwig, Hollomon, Voce, Swift and Krupkowski has been used to describe the plastic behaviour of polycrystalline metals and alloys. The Hollomon law in the form of:

$$\sigma = K\varepsilon^{n} \tag{3}$$

has been used most frequently. The parameters involved in this laws, particularly n-value has been, and continue to be, correlated to changes in the microstructure of a material and in some way represents processes which occur during deformation. They have also been used extensively to characterize the formability of sheet material.

The value of strain hardening exponent n is usually determined from the double logarithmic plot of the true stress and true strain by linear regression. When copper and brass sheets are concerned the logarithmic strain-stress relation is not a straight line – and that was observed in the case of 80-20 brass sheet under both the uniaxial (Fig. 3) and biaxial straining. The n-value is strain dependent what resulted from the changes in the crystallographic texture [7-9]. Because of this the mean n-value (which describe the strain hardening of the whole strain range) and differential n_t-value were determined on the base of results of uniaxial and biaxial testing.

Equation (3) assumes constant n-value and the average n-value is measured at a given strain range or can be determine for the whole range of straining from double logarithmic stress-strain data by a least squares approach. To examine the true strain hardening behaviors the instantaneous n_t-value should be determined. Taking the derivative from equation (3) yields:

$$\frac{d\sigma}{d\varepsilon} = Kn\varepsilon^{n-1} = \frac{\sigma}{\varepsilon} n \tag{4}$$

which results in

$$n_t = \frac{d\sigma}{d\varepsilon}\frac{\varepsilon}{\sigma} \tag{5}$$

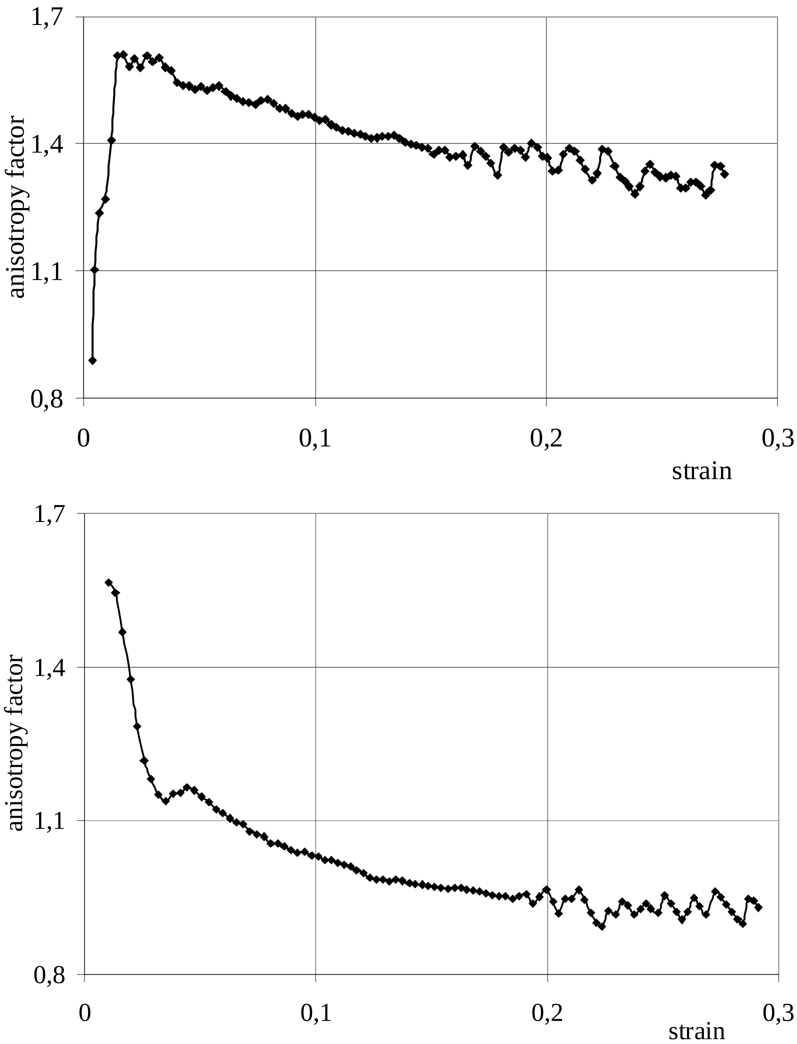

Fig. 1. Variation of r_t-value with strain for the 63-37 brass sheet specimens cut at 0° (upper) and 45° (lower) according to rolling direction

Rys. 1. Zmiany wartości wskaźnika r_t ze wzrostem odkształcenia blach ze stopu M63 dla próbek wyciętych pod kątem 0° (górny) oraz 45° (dolny) do kierunku walcowania

Variation of the n_t-value is strain and strain state dependent (Fig. 3). In the case of uniaxial testing of the 80-20 brass sheet the n_t-value riches its maximum at $\varepsilon = 0.15$, while in the case of biaxial stretching at $\varepsilon = 0.10$. These points could be treated as the beginning of quasistatical range of deformation process. The strain value of $\varepsilon = 0.36$ and $\varepsilon = 0.26$, for uniaxial and biaxial testing respectively, are the limit strains.

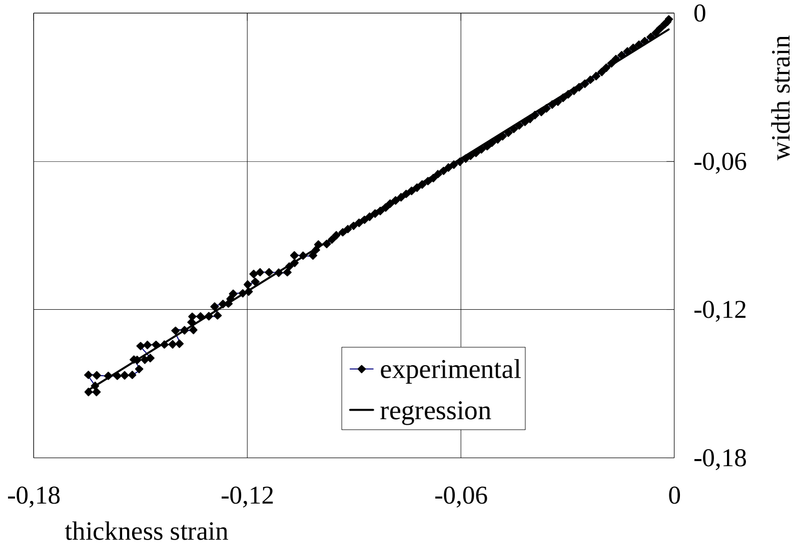

Fig. 2. Plastic anisotropy ratio of the 63-37 brass sheets determined by Welch et al. method

Rys. 2. Wartość współczynnika anizotropii blachy z mosiądzu M63 wyznaczona sposobem Welcha i in.

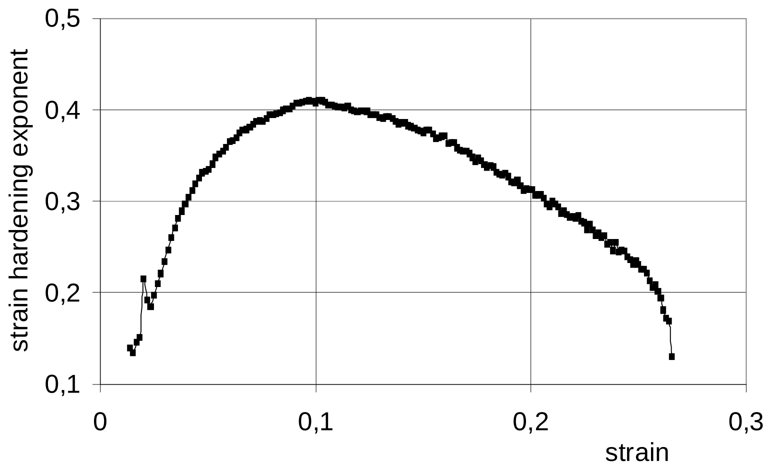

Fig. 3. Variation of n_t-value with strain for the 80-20 brass sheet, under uniaxial testing (cont. on p. 58)

Rys. 3. Zmiany wartości wskaźnika nt wraz ze wzrostem odkształcenia blach z mosiądzu M80 w próbie jednoosiowego rozciągania (cd. na str. 58)

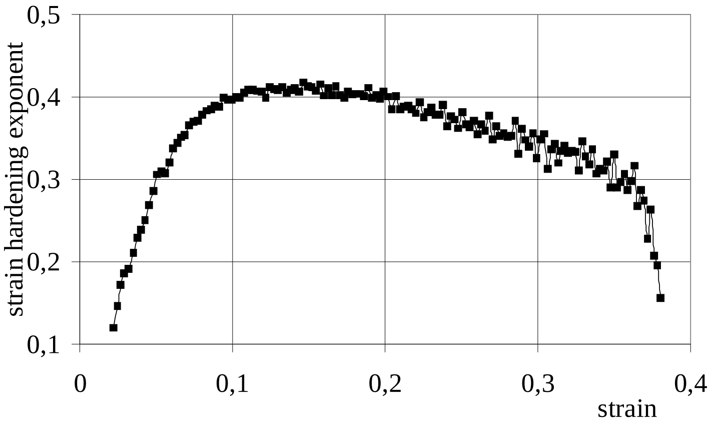

Fig. 3 (cont.). Variation of n_t-value with strain for the 80-20 brass sheet, under equibiaxial testing

Rys. 3 (cd.). Zmiany wartości wskaźnika nt wraz ze wzrostem odkształcenia blach z mosiądzu M80 w próbie dwuosiowego równomiernego rozciągania

Forming limit diagram calculation

The forming limit diagram (FLD) is today a generally accepted measure of sheet metal formability. It is extensively used in both scientific research and industrial practice. The FLD defines the extent to which a sheet can be strained before a sharp neck and final failure occur. The diagram presents the forming limit for a range of deformation modes ranging from deep drawing (negative minor strains, uniaxial tension) to stretch forming (positive minor strains, biaxial tension). The FLDs of the brass sheets were calculated basing on the M-K theory [10] – a sheet element was divided into two parts, region A with no material defects and region B, softened due to a presence of surface dimples and internal defects. The solution to the M-K problem was achieved in straight-forward incremental numerical procedure of calculations. In our calculations of the FLD we have used no fitting parameters to describe the inhomogeneity of a material, but we have based on experimentally obtained relations [11] which describe the material softening and strain localization processes.

When the influence of plastic anisotropy ratio on the FLD brass sheets is concerned, the following calculations were performed:

- calculations of the FLD using the value of mean normal anisotropy ratio r,
- calculations of the FLD using two different type of differential r_t-value and elongation relation – the increasing and decreasing function.

The FLD calculations using differential r_t-value as a two types of function of elongation (Fig. 4) has shown that in the $\varepsilon_2 > 0$ region increasing function of r_t-value resulted in decreasing of limit strains while when using the decreasing function the limit strains increase. This effect was the most visible for the equibiaxial stretching.

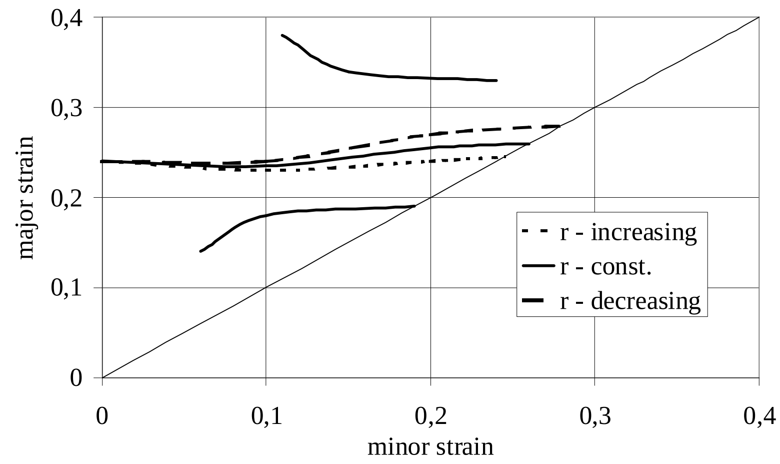

Fig. 4. Effect of differential anisotropy ratio changes (increasing and decreasing function of elongation) on the forming limit curve position

Rys. 4. Wpływ zmian chwilowych wartości współczynnika anizotropii (rosnąca oraz malejąca zależność od odkształcenia) na przebieg krzywych odkształcalności granicznej

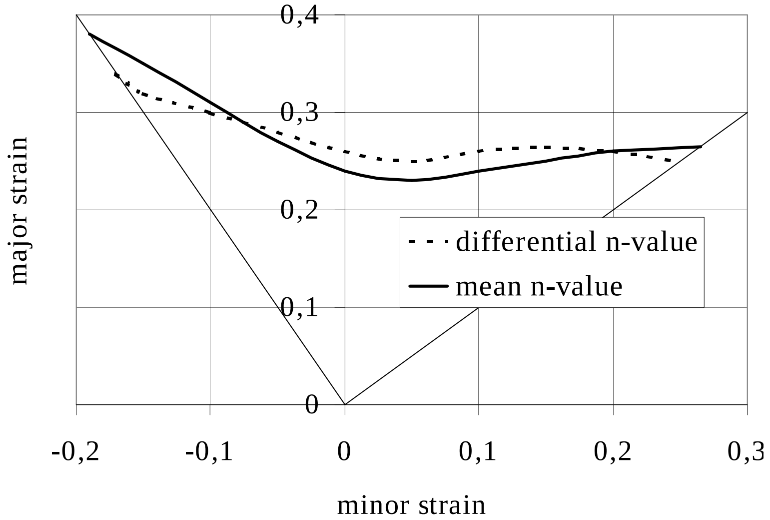

Fig. 5. FLCs calculated using mean n and differential n_t value of strain hardening exponent

Rys. 5. Krzywe odkształcalności granicznej obliczone przy założeniu średniej oraz chwilowych wartości wykładnika krzywej umocnienia odkształceniowego

As it was mentioned above the second important parameter affected the FLD is the strain hardening exponent. The knowledge of the differences in the hardening process during deformation seemed to be very useful in FLD calculations. Theoretically determined FLD presented in Fig. 5 demonstrate that forming limit curves calculated using both mean n-value and differential n_t-value are different in the shape. The FLC calculated using differential strain hardening exponent as a function of effective strain (Fig. 3) is more flat than that of the FLC calculated using mean n-value – however the position of these two FLC is very close.

Conclusion

The two most important material parameters – plastic anisotropy ratio (r) and especially strain hardening exponent (n) of brass sheets strongly depend on the strain state. Both the n and r parameters are strain dependent, so in some cases differential n_t and r_t value more precisely represent a material properties. These remarks should be taken into account in predicting sheet metal formability (forming limit diagram).

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WŁAŚCIWOŚCI PLASTYCZNE BLACH MOSIĘŻNYCH W PRÓBIE JEDNO- ORAZ DWUOSIOWEGO ROZCIĄGANIA

S t r e s z c z e n i e

Wartości wykładnika krzywej umocnienia odkształceniowego (n) oraz współczynnika anizotropii plastycznej (r) dwóch rodzajów blach mosiężnych zostały wyznaczone w próbach jedno- oraz dwuosiowego równomiernego rozciągania. Stwierdzono, że szczególnie wartość parametru n silnie zależy od wydłużenia próbki oraz od realizowanego stanu naprężenia/odkształcenia. Określono wpływ chwilowych (zależnych od stopnia odkształcenia) wartości wskaźników n_t oraz r_t na przebieg krzywych odkształcalności granicznej.

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