6th INTERNATIONAL MULTIDISCIPLINARY CONFERENCE

DETERMINATION OF FORMING LIMITS OF THIN ALUMINIUM SHEETS

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***Abstract**: An investigation concerning the mechanical properties and forming limit diagrams of the AW1050 aluminium sheets with different grain size has been carried out experimentally and analytically. The surface roughness growth with strain increasing was determined experimentally and applied to describe geometric inhomogeneity of the materials tested. The forming limit diagrams (FLD) have been determined experimentally using in-plane stretching test. The FLD were calculated based on the modified M-K theory using no fitting coefficient to describe material inhomogeneity. Calculated FLDs were compared with experimental results.*
***Key words:** forming limit, strain hardening, anisotropy, material inhomogeneity, surface roughness*

1. INTRODUCTION

To determine the amount of deformation a material can withstand prior to necking failure the concept of forming limit diagram (FLC) was introduced. There exist a great variety of methods for calculating the FLD for sheet materials forming. To be of practical value, theories of strain localization in sheet metal forming must be developed to give reliable representation of the influence of material inhomogeneity. Up to present, most analysis that take explicit account of material inhomogeneity have been based on the continuum model proposed by Marciniak and Kuczyński [1] in which it is assumed that there is a region of weakness in the form of a long band lying in the sheet plane. In most applications of this method (M-K) material inhomogeneity coefficient, f, has been chosen arbitrary to satisfy good correlation between experimental and calculated the FLD. In such analyses, the characterization of mechanical properties of a material i.e. strain hardening curve parameters and plastic anisotropy ratio, have been usually based on measurements in uniaxial tensile test.

Characterization of a material inhomogeneity, which initiates process of strain localization, is a separate problem, not less important than that of selecting appropriate form of yield locus. The M-K theory can be readily adopted to represent the influence of different kinds of material inhomogeneity provided that the assumption that the weak region in the form of a long band is retained. Plastic inhomogeneity that are capable to initiate process of strain localization leading to failure can occur in sheet metals in quite a wide variety of forms. Often it is directionality in the distribution of the inhomogeneity, rather than the macroscopic planar anisotropy of the sheet. However, when inhomogeneous straining is initiated in small compact regions essentially on the scale of the microstructure, then the growth and linking of the individual regions of strain concentration, leading to formation of a macroscopic band of strain localization.

When the mechanical properties of a material are concerned, the formability of a sheet metal has frequently been expressed by the value of strain hardening exponent, n, and plastic anisotropy ratio, r. The stress-strain behaviour of a material is very important in determining its resistance to plastic instability. In sheet metal forming operations uniaxial as well as biaxial strain state exist. Thus, one must know and understand material hardening behaviour as a function of strain state [2, 3]. Additionally the value of the n and r parameters depend on the grain size of a material and often changes as plastic deformation accumulates.

According to the Jonas and Baudelet work [4], the influence of geometrical defects on flow localization process is in an order of magnitude greater than that of mechanical (plastic) inhomogeneity. The necking process in sheet metal forming can be initiated by different types of geometric inhomogeneity, as non-homogeneous distribution of internal inclusions or surface roughness of sheet metal. In part, surface roughness is a microstructural manifestation of the slip events that occur during deformation that lead to necking and subsequent failure at large strains [5]. According to the author's work [6] geometric inhomogeneity caused by surface roughness seems to be more important factor affected limit strain level than the inhomogeneity component caused by internal defects.

The intent of this work was to examine the mechanical behaviour of a material and the geometric inhomogeneity of AW1050 aluminium sheets and apply these results in the calculations of the FLDs. Theoretical calculations will be performed on the base of the M-K theory using the flow theory of plasticity - the coefficient of a material inhomogeneity will be determined on the base of experimental results. The calculated FLDs will be compared with experimental ones.

2. MATERIALS AND MECHANICAL TESTING

The present investigations have been carried out using the 1.0 mm thick AW1050 commercially pure aluminium sheets annealed to produce different grain size. The symbols of the materials used in experiments are as follow:

- A-1 for sheet with 39.1 μm average grain diameter,
- A-2 for sheet with 55.9 μm average grain diameter.

The tensile specimens of 40 mm length and 20 mm width were prepared from the strips cut at 0^o, 45^o and 90^o according to the rolling direction of the sheet. The experiments were carried out using a special device that recorded simultaneously the tensile load, the current length and width of a specimen. In order to determine the flow properties of the aluminium sheets in equibiaxial 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.

The yield stress, ultimate strength, total elongation, plastic anisotropy ratio, r, and strain hardening parameters, K and n, in the Hollomon equation $\sigma = K\ \varepsilon^n$ were determined on tests results. In the case of both the tensile and equibiaxial tests the value of strain hardening parameters were determined from double logarithmic presentation of flow curve. The value of all above mentioned parameters summarized in Table 1 has been averaged according to:

$$x_{mean} = 1/4(x_0 + 2x_{45} + x_{90}) \qquad (1)$$

The value of plastic anisotropy ratio, r, is usually determined at a given specimen elongation. However there has been interest in the effect of specimen elongation on the value of r-value while acknowledging that the changes in the crystallographic texture occurred with strain increasing. For plasticity studies, the basic definition of plastic anisotropy ratio $r = \varepsilon_w/\varepsilon_t$ has been replaced with the instantaneous (differential) r_t-value defined as $r_t = d\varepsilon_w/\varepsilon_t$. According to the latest experimental results [6, 7] no systematic increases 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 different specimen orientation have shown that in the case of aluminium sheets no clear correlation between differential plastic anisotropy ratio and specimen elongation exists. Because of that the r-value was determined using Welch et al. [8] method, and it could be treated as a reasonable representation of anisotropic behaviour over a wide range of specimen elongation.

Table 1. Mechanical properties of AW1050 aluminium sheets

Material	Yield stress	Ultimate strength	Plastic anisotropy coefficient	Tensile strain hardening parameters		Equibiaxial strain hardening parameters	
	MPa	MPa		K, MPa	n	K, MPa	n
A - 1	43.4	82.4	1.22	116	0.265	153	0.227
A - 2	46.6	95.2	0.96	130	0.278	155	0.253

3. DEVELOPMENT OF SURFACE ROUGHNESS

Inhomogeneous deformation of grains situated close to a free surface of a sheet metal is a general effect of incompletely constrained deformation that gives rise to a well-known form of surface roughening [9÷11]. Plastic deformation roughens a free surface by producing, among other things, slip bands within grains along with relative rotation and sliding among grains. For the room tests the surface vertical roughness increases in linear proportion to the magnitude of plastic deformation and the average grain size of the test specimen, while it is independent of stress mode and strain rate.

The surface roughness of the material tested was measured during step by step deformation by means of a mechanical stylus type profilometer with a tip radius of 5 μm, at the interval of about 0.02 of applied strain. As it should be expected the value of the surface roughness parameter Rmax increased linearly with strain increasing - the more intensively the larger grain size a material possesses (Fig. 1). From this presentation it is also visible that at large strain the value of surface roughness parameter Rmax started to accelerate. The value of the strain at the moment of acceleration could be treated as the limit strain.

Calculation of surface roughness parameter in relation to grain size and applied specimen elongation, performed according to Fukuda et. al. [9] equation demonstrated deviation from linearity. The surface roughness versus the effective strain and grain diameter relation could be better described using modified equation [12]:

$$R = R^o + k\varepsilon_e d^{0.5} \qquad (2)$$

where: R^o - the value of surface roughness parameter of undeformed sheet,

ε_e - effective strain,

d - average grain diameter,

k - material constant.

For AW1050 sheets the value of the k-parameter of the above mentioned equation (2) was found as follow:

- k = 2.879 $\mu m^{0.5}$ for the A-1 sheet,
- k = 2.884 $\mu m^{0.5}$ for the A-2 sheet,

what confirm that the k-parameter do not depend on material grain size and could be treated as a material constant.

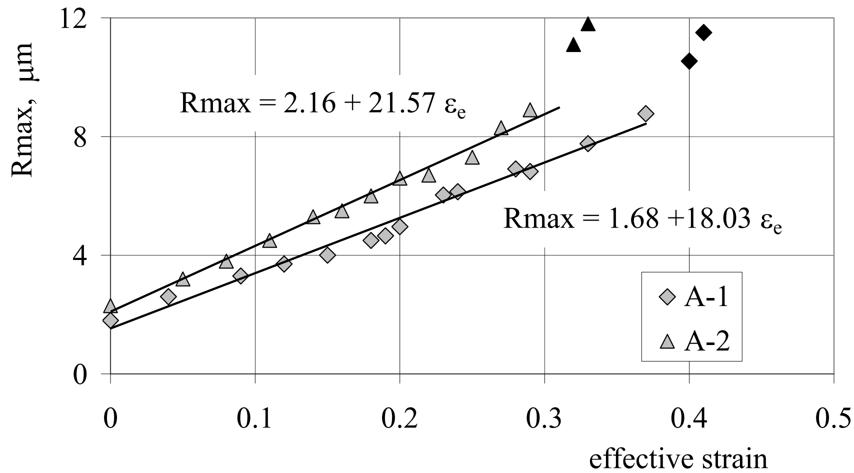

Fig. 1. *Surface roughness versus specimen elongation for fine grained A-1 and coarse-grained A-2 aluminium sheets*

4. DETERMINATION OF THE FLDs

Experimental FLDs were determined using in-plane stretching test over flat-bottomed rigid punch. Sheet blanks 250 mm in length and with successively narrower widths enabled to produce different strain ratio $\rho = \varepsilon_2/\varepsilon_1$. A circular grid was imposed on the sheet surface with circle diameter of 2.42 mm. The test was continued until a crack or visible necking occurs on the sheet surface. For each specimen the true major ε_1 and minor ε_2 strains were measured on the circles adjacent to the crack or visible necking but not crossing it. The presence of a few cracks on the gauge area of specimens was observed, what enabled to choose several measuring points (in contrast to stretching over hemi-spherical punch where the straining concentrates only near the punch top).

Calculation of the FLDs were performed according to the M-K theory. The analysis is based on the consideration of thickness non-uniformity in the form of a band inclined at an angle ψ with respect to the principal direction of stress and strain rate state. In the biaxial stretching range ($\rho = \varepsilon_2/\varepsilon_1/0$) the band inclination angle $\psi = 0$. Outside the band these principal directions are further assumed to remain fixed, parallel to a material coordinate system. In our calculations we have used no fitting parameters to describe material inhomogeneity. The sheet thickness in the bulk material and band are interrelated by

$$t_{band} = t_{bulk} - 2R\max \tag{3}$$

It was assumed that the material inhomogeneity coefficient, $f = t_{band}/t_{bulk}$, is not a constant value but changes with strain increasing.

The calculations were based on the flow theory and quadratic Hill's yield function. The solution to the M-K problem was achieved in straight-forward incremental procedure of calculations. For every step, a strain increment $d\varepsilon_1$ was imposed to the bulk material, and the rest of the strain increments were calculated to satisfy geometrical conditions and the force balance across the band. The criterion for convergence in the iterative solution was that the value of strain increment in the band does not change significantly by applying further iterations. The tolerance value determined the precision of the calculations; smaller tolerance resulted in more precise calculations but with larger computation time. The final results did not depend heavily on the tolerance, which, in these calculations, was set at 0.0001.

Quite good correlation between calculated and experimental FLDs of the aluminium sheets (Fig. 2) resulted from some improvements in calculations procedure. In these calculations the values of strain hardening exponent in both the tensile, n^t, and equibiaxial, n^b, tests were applied (the position of the FLD almost do not depend on the value of strain hardening coefficient K). For the strain range $-0,5 < \rho = \varepsilon_2/\varepsilon_1 < 1.0$ the n-value was calculated according to the early determined [5] equation:

$$n = n^b - 2\rho(n^t - n^b) \tag{4}$$

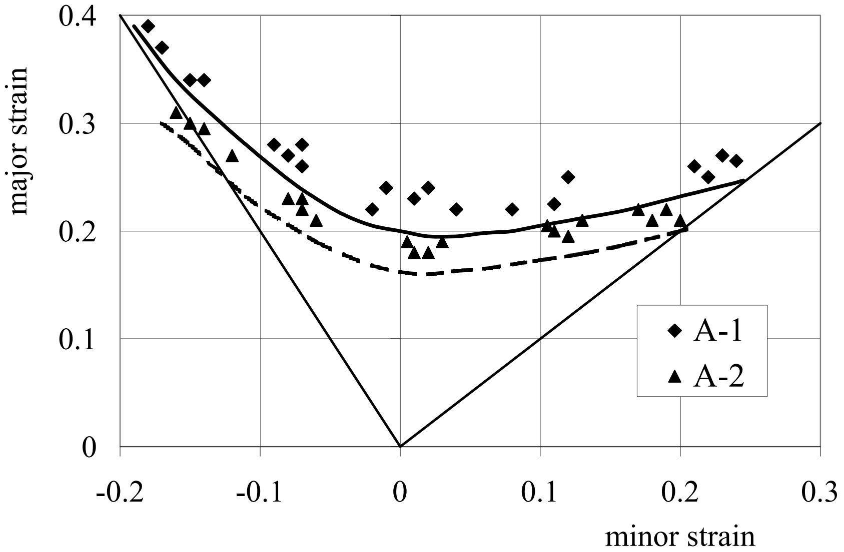

Fig. 2. *Comparison between experimental (points) and calculated (lines) forming limit curves of fine grained A-1 and coarse-grained A-2 aluminium sheets*

5. CONCLUSIONS

The value of strain hardening coefficient, very important parameter affected the value of limit strains, demonstrated visible strain state dependence – for both materials the tensile strain hardening exponent values are larger than that determined in bulge test.

Plastic deformation roughens a sheet surface in the proportion to the equivalent strain and the square root from the average grain diameter of a material.

The FLDs of the AW1050 commercially pure aluminium sheets calculated according to the M-K theory and using no material inhomogeneity factors (material inhomogeneity was expressed by surface roughness parameter) are in close relation to experimental results.

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