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FORMING LIMIT DIAGRAM OF THE AMS 5599 SHEET METAL

KRZYWA ODKSZTAŁCALNOŚCI GRANICZNEJ BLACHY ZE STOPU AMS 5599

Formability of sheet metal is dependent on the mechanical properties. 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 and plastic anisotropy ratio. The stress-strain and hardening behaviour of a material is very important in determining its resistance to plastic instability. However experimental studies of formability of various materials have revealed basic differences in behaviour, such as the "brass-type" and the "steel-type", exhibiting respectively, zero and positive dependence of forming limit on the strain ratio. In this study mechanical properties and the Forming Limit Diagram of the AMS 5599 sheet metal were determined using uniaxial tensile test and Marciniak's flat bottomed punch test respectively. Different methods were used for the FLD calculation – results of these calculations were compared with experimental results.

Keywords: sheet metal, forming limit, strain hardening, plastic anisotropy

Zdolność do przyjmowania odkształceń plastycznych podczas kształtowania blach zależy od ich właściwości mechanicznych. Odkształcalność blach zależy od rodzaju materiału – a ponadto, materiał który wykazuje dobrą odkształcalność podczas kształtowania wytłoczki o określonej geometrii, może sprawiać trudności podczas kształtowania wytłoczki o innej konfiguracji. Z tego powodu prowadzone są liczne prace badawcze mające na celu określenie relacji pomiędzy odkształcalnością blach a wartością parametrów mechanicznych materiału. Przy ocenie odkształcalności blach najczęściej korzysta się z wyznaczania wartości wykładnika krzywej umocnienia odkształceniowego oraz współczynnika anizotropii właściwości plastycznych. Znajomość charakterystyk odkształcenie-naprężenie oraz wskaźników umocnienia odkształceniowego jest bardzo ważna przy określaniu odporności na lokalizację odkształcenia. Badania eksperymentalne blach z różnych materiałów wykazały zasadnicze różnice ich odkształcalności, określane jako "typu mosiądz" oraz "typu stal", przejawiające się brakiem lub wyraźną zależnością poziomu odkształceń granicznych od stanu odkształcenia. W pracy zawarte są wyniki badania właściwości mechanicznych w próbie jednoosiowego rozciągania oraz KOG w teście wg Marciniaka z płaskim stemplem, dla blachy ze stopu AMS 5599. Przeprowadzono obliczenia przebiegu krzywej odkształcalności granicznej przy pomocy różnych metod – wyniki obliczeń porównano z wynikami eksperymentu.

1. Introduction

The sheet metal forming processes basically involve large amounts of plastic deformation, and due to the complexities of plasticity, the exact analysis of a process is infeasible in most of the cases. Thus, a number of approximate methods have been suggested, with varying degrees of approximation and idealisation [1-5]. An estimation of how close the metal is to failure can be obtained by reference to the forming limit diagram (FLD), which is a plot of the major- and mi-nor- surface strain in the vicinity of fracture over a wide range of conditions, from deep drawing (tension-compression) to stretch forming (tension-tension). The knowledge of how close the metal is to failure enables an estimation to be made of the criticality of the press-forming operation. The strain values and the ratio of minor- and major-strain give valuable information on the type of deformation that has occurred in various areas of the press-formed part e.g. whether the metal has been drawn or stretched. Sheet metal forming under multiaxial states of stress, as in sheet metal operations, usually fails by localized necking. The current interest in understanding sheet metal formability has led to several theoretical analyses of localized necking based on different criteria. The popular methods are Hill's local instability [6] and Swift's diffuse instability criteria [7] for isotropic materials. The localized necking criteria include; a localized shear zone along a direction of zero-extension [6], materials imperfection [8], the presence of a vertex on the yield surface [9] and void growth [10]. It has been proven that for some sheet materials a good simulation of the forming limit strains can be given on the basis of the

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Hill's and Swift's theories used to calculate the forming limit strains on the left and the right side, respectively, of the FLD. Assuming that the strain-stress relationship of sheets can be expressed by Hollomon's equation the formulae calculating the forming limit strains can be written as follows, with stress ratio $\alpha = \sigma_2/\sigma_1$:

For $\varepsilon_2 < 0$:

$$\varepsilon_{1L} = n\frac{1 + (1-\alpha)\, r}{1+\alpha} \tag{1}$$

$$\varepsilon_{2L} = n\frac{\alpha - (1-\alpha)\, r}{1+\alpha} \tag{2}$$

For $\varepsilon_2 > 0$:

$$\varepsilon_{1L} = n\frac{(1 + r_0 - r_0\alpha)\left[1 + r_0 + \alpha^2\left(\frac{r_0}{r_{90}}\right)(1 + r_{90}) - 2\alpha r_0\right]}{(1 + r_0 - r_0\alpha)^2 + \alpha\left(\alpha\frac{r_0(1+r_{90})}{r_{90}} - r_0\right)^2} \tag{3}$$

$$\varepsilon_{2L} = n\frac{(1 + r_0 - r_0\alpha)\cdot\left[\alpha + \alpha r_0 - \alpha^2\cdot r_0 + \alpha\left(\frac{r_0}{r_{90}}\right)(1 + r_{90}) - r_0\right]}{(1 + r_0 - r_0\alpha)^2 + \alpha\left(\alpha\frac{r_0(1+r_{90})}{r_{90}} - r_0\right)^2} \tag{4}$$

Strain localization development by local weakness of material was first proposed by Marciniak and Kuczyński [8], as a mean of describing localized necking in biaxial stretching. The M-K analysis assumes the presence of material imperfection in the form of a groove. M-K has shown that deformation within groove occurs at a faster rate than the rest of the sheet. The concentration of strain within the groove eventually leads to the plane strain condition within the groove and localized necking. The M-K model is thus able to explain localized necking in biaxial stretching.

However experimental studies of formability of various materials have revealed basic differences in behaviour, such as the ”brass-type” and the ”steel-type”, exhibiting respectively, zero and positive dependence of forming limit on the strain ratio [11]. Calculations of the forming limit diagram (FLD) according to different methods lead to the general conclusion that in the case of steel sheets the value of calculated limit strains was visibly smaller than the experimental results.

For several materials like copper, low carbon steel, and aluminium some authors [12-16] have proposed assessing the formability of sheet metals based on states of stress rather than state of strain. They constructed the forming limit stress curve (FLSC) by plotting the state of stress at the onset of localized necking in stress space. They found that the FLSC is almost path-independent and can be established, either experimentally or analytically, and then the limits to formability will be predicted accurately, not only for proportional loading but also in cases where a sheet element has a complex strain history.

Sing and Rao [17] has proposed a novel approach for the prediction of the FLSC, which is based entirely on material properties readily measured from only tensile test. Starting from the knowledge of a single limit yield stress, a continuous yield locus based on Hill's anisotropic yield criterion could be developed, and, subsequently, a linear limit yield stress state locus could be obtained using the linear regression technique. From this FLSC, the corresponding FLC can, in turn, be deducted using the appropriate strain-hardening law, associated flow rule, and Hill's general criterion. On the base of flow rule the surface limit strains for different stress (or strain) ratio could be calculated as:

$$\begin{aligned}\varepsilon_{1L} &= \left[(1+2r)(\sigma_{1L} - \sigma_{2L}) + (\sigma_{1L} + \sigma_{2L})\right]\lambda \\ \varepsilon_{2L} &= \left[-(1+2r)(\sigma_{1L} - \sigma_{2L}) + (\sigma_{1L} + \sigma_{2L})\right]\lambda\end{aligned} \tag{5}$$

where:

$$\lambda = \frac{\varepsilon_{eL}}{2(1+r)\,\sigma_{eL}} \tag{6}$$

According to the original Sing-Rao proposition the FLSC could be obtained using the linear regression technique based on the results of calculation using above mentioned scheme taking into account mean plastic anisotropy ratio. However in our calculation we have made some modification taking into account different specimen orientation according to rolling direction [18] and we suggest that this modification should result in better determination of the FLSC.

In this study mechanical properties and forming limits of the AMS 5599 sheet metal were determined using uniaxial tensile test and Marciniak's flat bottomed punch test respectively. Comparison between some material characteristics of the material tested and the extra deep drawing steel sheet used in automobile industry as well as brass sheet is performed.

2. Experimental materials and methods

The AMS 5599 heat resistant sheet metal, 0.6 mm thick were used in this experiment. When the mechanical testing is concerned, tensile specimens of 240 mm gauge length and 12.5 mm width were prepared from strips cut at 0°, 45° and 90° 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 the current width of the specimens. The effective stress – effective strain relationship was described using the Hollomon model.

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:

$$r = \frac{\varepsilon_w}{\varepsilon_t} \tag{7}$$

The r-value at a given elongation, usually 15 pct (ε= 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:

$$r_t = \frac{d\varepsilon_w}{d\varepsilon_t} \tag{8}$$

According to the latest experimental results [19-23] no systematic increase or decrease of r_t-value with strain was observed, in contrast to previous reports in the literature. And because of that the r-value has been determined on the base of the relationship between the width strain and thickness strain in the whole range of specimen elongation according to the method proposed by Welch et al. [24], and it could be treated as a reasonable representation of anisotropic behavior over a wide range of elongation.

In the present investigation, the FLD was determined using in-plane stretching test over rigid punch, according to the method proposed by Marciniak et al. [25]. This method is characterised by (i) the elimination of the friction between the specimen and tool surface, which enables realisation of homogeneous straining in the wide region of the sheet tested: and (ii) the retention of the flat surface of the specimen during the straining process, which enables more convenient and more precise measurements of the strain value to be made. Sheet blanks 250 mm in length and successively narrower width afforded a range of different strain ratios. A circular grid was marked on the sheet surface in the central part of the specimens. The driving blanks were prepared from the same material as the specimens, the central hole in the driving blank is 52 mm in diameter. The test was continued until a crack or necking was visible on the specimen surface, at that moment the test being interrupted. The presence of a few small crack or visible grooves on the gauge area of the deformed specimen's surface confirmed the homogeneous straining of the sheet. The true major strain ε_1 and minor strain ε_2 were measured on the circle adjacent to the crack or visible groove, but not crossing it: this means that the measured circle includes the relatively homogeneously strained area, away from the crack. On the base of these results the FLD was obtained.

3. Results and discussion

The value of the tensile parameters (Table 1) has been averaged according to: $x_{mean} = (x_0+2x_{45}+x_{90})/4$: where the subscripts refer to specimen orientation. On the base of these results we can conclude that the AMS 5599 sheet material is high strength and very sensitive to strain hardening. It is characterized by small value of plastic anisotropy factor, especially determined for specimens cut in the rolling direction of the sheet plate. Uniaxial tensile characteristic of the AMS 5599 steel seems like that obtained for brass sheet (Fig. 1) with the value of uniform strain close to value of total strain and visibly differ from the EDDQ steel sheet characteristic.

TABLE 1

Mechanical properties of the AMS 5599 sheet metal

Specimen orientation	Yield stress	Ultimate strength	Total elongation	Strain hardening parameters		Anisotropy factor
	$R_{0,2}$ MPa	R_m MPa	A_{50}	C MPa	n	r
0^0	392	1007	0.40	1897	0.316	0.557
45^0	385	974	0.45	1833	0.314	1.118
90^0	387	986	0.45	1817	0.296	0.986
Mean value	388	985	0.44	1845	0.310	0.945

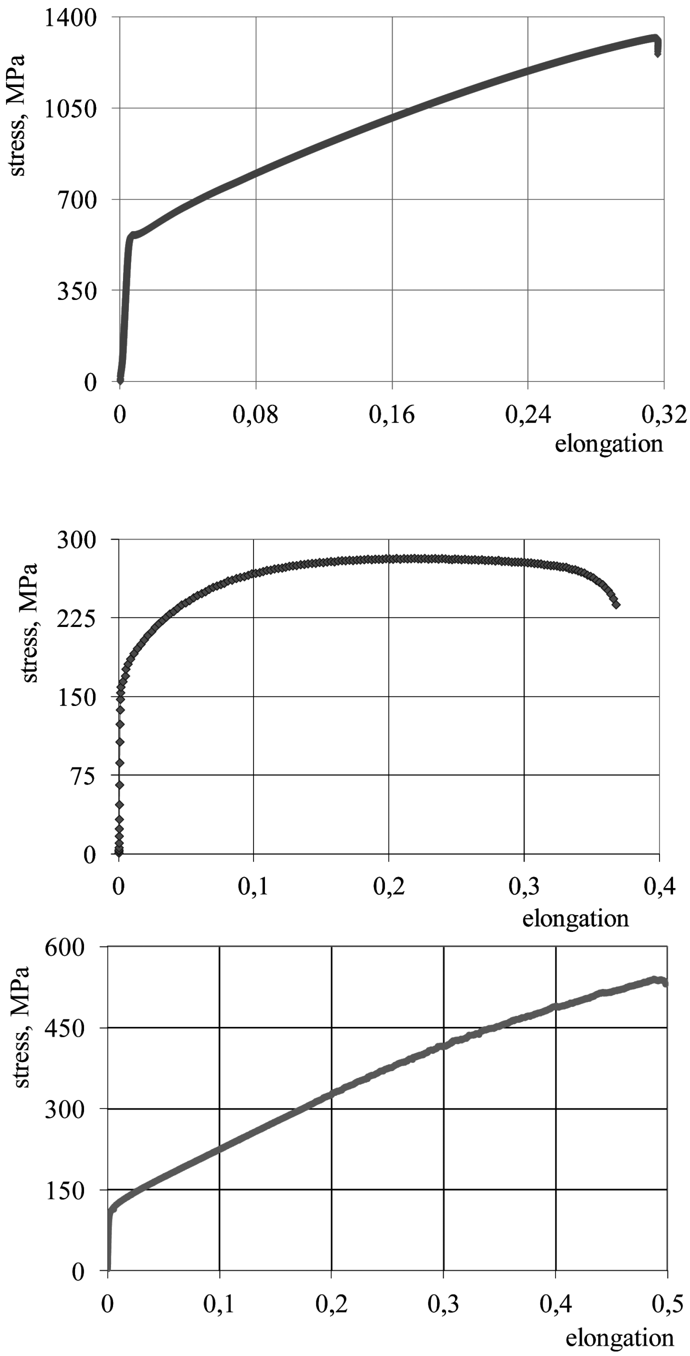

Fig. 1. Comparison of the uniaxial tensile characteristics of the AMS 5599 (upper), EDDQ steel (middle) and 63-37 brass (lower) sheet metal

On the base of the material tensile testing results the FLC was calculated taking into account four different methods: by Hill, Swift, Marciniak-Kuczyński and Sing-Rao. In the case of M-K method the value of material imperfection coefficient increase with strain increasing [19, 26] and was defined as:

$$f = 1 - \frac{Ra}{t} \qquad (9)$$

where: Ra = 0.2 μm – is surface roughness parameter, t – sheet thickness.

Comparison between experimentally determined and calculated forming limit curves (Fig. 2) visibly demonstrates that the best correlation with experiment was obtained for

FLC calculated using Hill and Swift methods, although results of such calculation could not be treated as satisfied for different application, for example for numerical modelling of sheet forming processes. Calculations of FLC on the base of Marciniak-Kuczyński method underestimate the value of limit strains while calculation on the base of Sing-Rao method overestimate the value of limit strains.

Experimentally determined FLD as well as mechanical properties of the AMS 5599 sheet was compared with two sheet material very suitable for deep drawing processes namely the EDDQ steel and 63-37 brass sheet metal (Fig. 3 and Table 2). The level of limit strains of the AMS 5599 sheet is unexpectedly smaller than of steel and brass sheets (Fig. 3) taking into account their value of strain hardening exponent and (Table 2). This situation could be explained as a result of small value of plastic anisotropy ratio of the AMS 5599 sheet.

The product of strain hardening exponent and plastic anisotropy factor, n·r index, could be used as a measure of sheet metal formability. In the case of compared materials, i.e. the AMS 5599, EDDQ steel and 63-37 brass, very good correlation between the value of n·r index and the value of strain limit in plane strain, FLD_0 index, was found (Table 2).

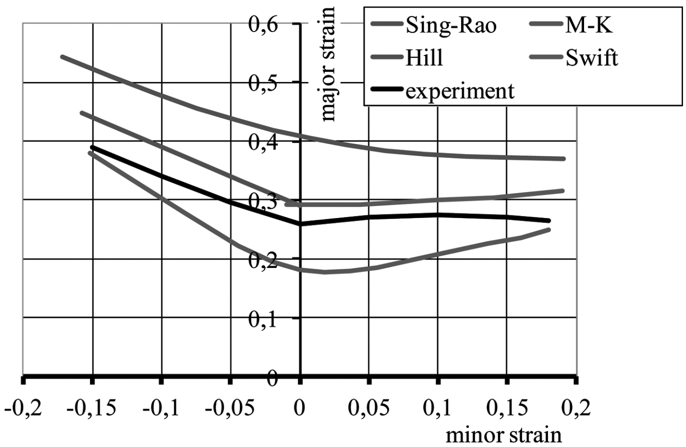

Fig. 2. Comparison of experimental and calculated forming limit curve of the AMS 5599 sheet metal

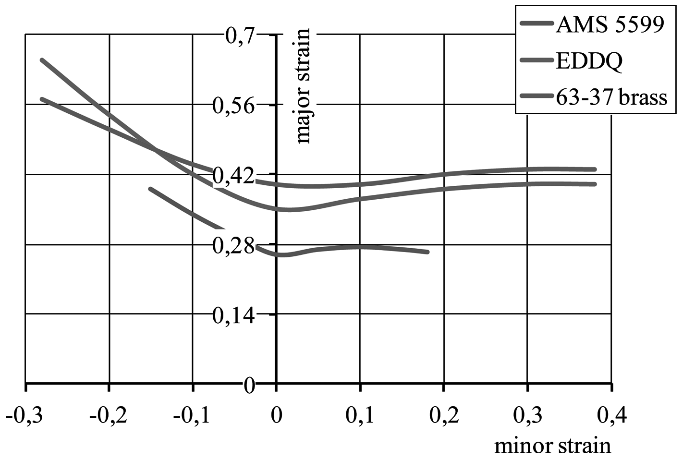

Fig. 3. Comparison of the forming limit curve of the AMS 5599, EDDQ steel and 63-37 brass sheet metal

4. Conclusion

Mechanical properties and forming limit diagram of the AMS 5599 heat resistant sheet metal is investigated in this study. On the basis of the experimental results and calculations the following conclusions could be formulated:

- The AMS 5599 sheet material is high strength and very strain sensitive to strain hardening. It is characterized by small value of plastic anisotropy factor. The value of uniform strain at uniaxial testing is very close to value of total strain.
- The best correlation with experimental results was obtained for the FLC of the AMS 5599 calculated using Hill and Swift methods, although results of such calculation could not be enough satisfied.
- The level of limit strains of the AMS 5599 sheet is unexpectedly small in comparison with the FLD of the EDDQ steel and 63-37 brass sheets.
- Very good correlation between the value of n·r index and the value of strain limit in plane strain, FLD_0 index, was found in the case of compared materials.

TABLE 2

Comparison of the mechanical properties and forming limit strain index of the AMS 5599, EDDQ steel and 63-37 brass sheet metal

Material	Yield stress	Ultimate strength	Total elongation	Strain hardening parameters		Normal anisotropy factor	Material index	Limit strain index
	$R_{0,2}$ MPa	R_m MPa	A_{50}	C MPa	n	r	n·r	FLD_0
AMS 5599	388	985	0.44	1845	0.310	0.945	0.293	0.26
EDDQ steel	187	329	0.37	571	0.213	1.722	0.367	0.35
63-37 brass	123	349	0.48	781	0.516	0.856	0.442	0.40

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