Formability of the austenitic nickel-base super alloy AMS 5596 sheet in comparison with extra deep drawing quality steel sheet

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Abstract

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. The forming limit of a metal sheet is generally given in terms of the limiting principal strains under different loading conditions and represented by the so-called forming limit diagram FLD. In view of the difficulty to experimentally determine the forming limits many researchers have sought other methods to predict FLD. 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. For these reasons, extensive test programs are often carried out in an attempt to correlate material formability with value of some mechanical properties. In this study mechanical properties and the Forming Limit Diagram of the AMS 5596 sheet metal were determined using uniaxial tensile test and Marciniak's flat bottomed punch test respectively.

1 Introduction

The need for accurate material characterisation methods is of great importance in order to further strengthen the use of the simulation technique for sheet metal forming applications. Much work has been made during the last years in order to increase the accuracy of finite element programs and modelling technique. One area of significant importance in order to further increase the correlation between simulations and reality is the experimental determination of relevant material properties [1]. This is becoming of even more important due to increased use of new high strength materials in order to reduce weight and increase the operate performance. The problem with these high strength materials is that their increase strength is usually compensated by a reduction in formability.

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 minor- 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 deBformation 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]. In view of the difficulty to experimentally determine the forming limits many researchers have sought to predict FLD basing on the specific material parameters determined in standard material tests with application of different theories [11]-[13].

In this study comparison between some material characteristics and forming limit diagram of the austenitic nickel-base super alloy AMS 5596 and the extra deep drawing EDDQ steel sheet used in automobile industry is performed. Mechanical properties were determined using uniaxial tensile test and forming limits using Marciniak's flat bottomed punch test.

2 Experimental materials and methods

The austenitic nickel-base super alloy AMS 5596 (Aerospace Material Specification) sheet (0.6 mm thick) and extra deep drawing quality EDDQ steel sheet (0.8 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.

In the present investigation, the FLD was determined using in-plane stretching test over rigid punch (Fig. 1), according to the method proposed by Marciniak et al. [14]. 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 cracks 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 basis of these results the FLD was obtained.

3 Results and discussion

On the base of these results we can conclude that the AMS 5596 sheet is high strength material and very sensitive to strain hardening. It is characterized by a low value of plastic anisotropy factor, especially determined for specimens cut in the rolling direction of the

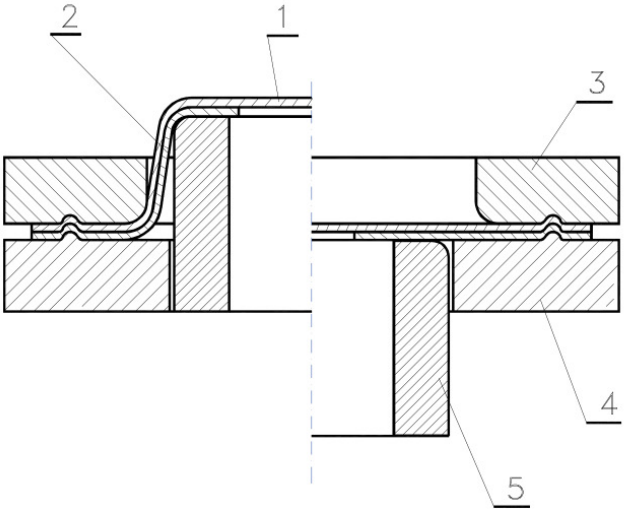

Figure 1: Scheme of Marciniak's in plane test for FLD determination: 1 - specimen, 2 - spacer, 3 - blankholder, 4 - die, 5 - punch

sheet plate. Uniaxial tensile characteristic of the AMS 5596 sheet with the value of uniform strain close to value of total strain visibly differs from the EDDQ steel sheet characteristic (Fig. 2). The value of the tensile parameters (Table 1 and 2) has been averaged according to: $x_{mean} = (x_0 + 2x_{45} + x_{90})/4$: where the subscripts refer to specimen orientation.

Table 7: Mechanical properties of the AMS 5596 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°	509	940	0.39	1862	0.315	0.552
45°	495	915	0.43	1843	0.314	0.997
90°	518	929	0.41	1840	0.319	0.907
Mean value	504	925	0.41	1846	0.316	0.863

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 ($\varepsilon = 0.14$) 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:

$$r = \frac{d\varepsilon_w}{d\varepsilon_t}. \tag{2}$$

Table 8: Mechanical properties of the EDDQ steel 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°	151	282	$0,44$	494	$0,221$	$1,630$
45°	153	293	$0,40$	497	$0,207$	$1,445$
90°	153	281	$0,42$	475	$0,210$	$2,031$
Mean value	153	287	$0,42$	487	$0,211$	$1,638$

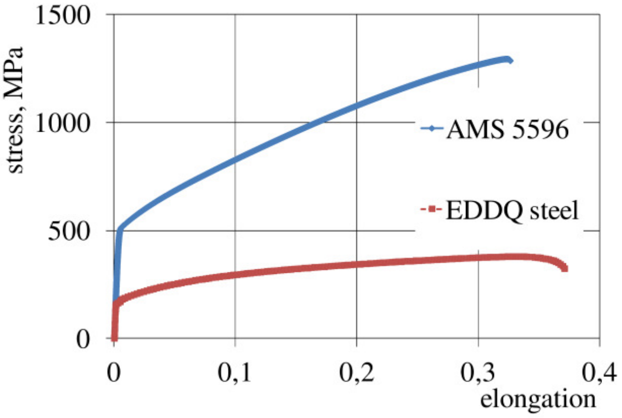

Figure 2: Comparison of the uniaxial tensile characteristics of the AMS 5596 and EDDQ steel sheet

According to the latest experimental results [15]-[19] no systematic increase or decrease of r_t-value with strain was observed, in contrast to previous reports in the literature. The test results of the instantaneous r_t-value determination for materials tested (Fig. 3) have shown that no clear correlation between plastic anisotropy ratio and specimen elongation exists. And because of that the r-value has been determined on the basis 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. [20], and it could be treated as a reasonable representation of anisotropic behaviour over a wide range of elongation.

For many years strain hardening laws such as those from Ludwig, Hollomon, Voce, Swift and Krupkowski have 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 the most frequently. The parameters involved in this law, 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. The n-value is strain dependent what resulted from the changes in the crystallographic texture [15], [20]-[22]. 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 the results of uniaxial and biaxial testing.

Equation (3) assumes a constant n-value and the average n-value is measured at a given strain range. 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:

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

The results presented in Figure 4 show clearly that there is no unique constant n-value which may characterize hardening process. The differential n_t-value varies continuously with specimen elongation:

- in the case of AMS 5596 sheet increases at strains up to $\varepsilon = 0.2$ and at higher strains falls rapidly,
- in the case of EDDQ steel sheet increases at small strains up to $\varepsilon = 0.1$, then stabilse on a certain level and at higher strains $\varepsilon > 0.3$ falls rapidly.

The level of limit strains of the AMS 5596 sheet is unexpectedly smaller than that of the EDDQ steel sheet (Fig. 5) when taking into account their value of strain hardening exponent (Table 1). This situation could be explained as a result of small value of plastic anisotropy ratio of the AMS 5596 sheet in comparison to value of plastic anisotropy ratio of the EDDQ steel sheet, especially in the case of specimen cut in rolling direction (Table 1 and 2). The product of strain hardening exponent and plastic anisotropy factor, $n \cdot r$ index, could be used as a measure of sheet metal formability. In the case of compared materials, i.e. the AMS 5599 and EDDQ steel, very good correlation between the value of $n \cdot r$ index and the value of strain limit in plane strain, FLD_0 index, was found (Table 3).

4 Conclusions

On the basis of the experimental results and calculations the following conclusions could be formulated:

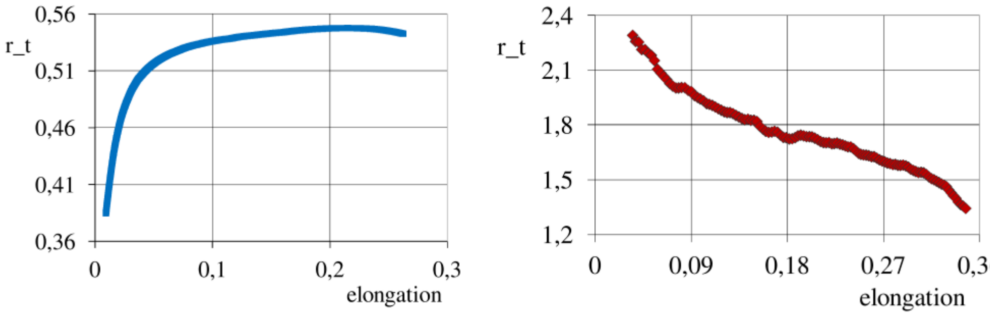

Figure 3: Variation of r_t-value with strain for the AMS 5596 sheet specimen (left) and EDDQ steel sheet specimen (right) cut in rolling direction

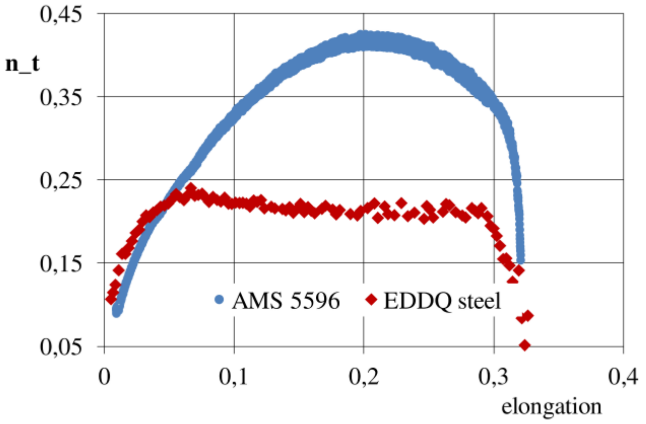

Figure 4: Variation of n_t-value with elongation of the AMS 5596 and EDDQ steel sheet metal.

Table 9: Comparison of the mechanical properties and forming limit strain index of the AMS 5596 and EDDQ steel sheet

Material	Strain hardening parameters		Normal anisotropy factor	Material index	Limit strain index
	C MPa	n	r	$n \cdot r$	FLD_0
AMS 5596	1846	0.316	0.863	0.273	0.26
EDDQ steel	487	0.211	1.638	0.346	0.35

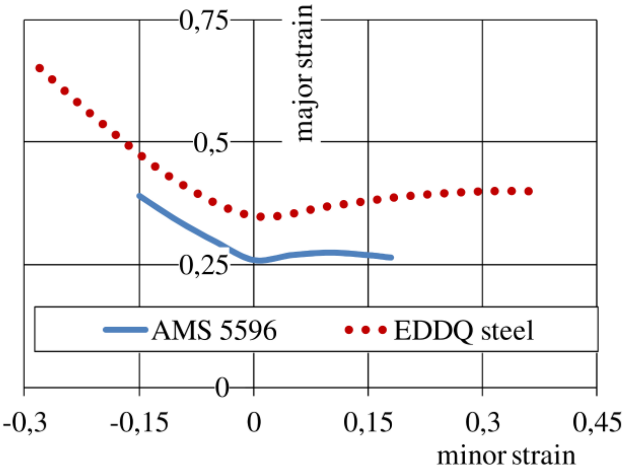

Figure 5: Comparison of the forming limit curve of the AMS 5596 and EDDQ steel sheet metal

- The AMS 5596 sheet material is high strength and very strain sensitive to strain hardening. It is characterized by a low value of plastic anisotropy factor. The value of uniform strain at uniaxial testing is very close to value of total strain.

- The level of limit strains of the AMS 5596 sheet is unexpectedly low in comparison with the FLD of the EDDQ steel sheet.

Acknowledgment

This work was supported by the National Centre for Research and Development - grant No. INNOTECH-K1/IN1/3/156571/NCBR/12.

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