Deformation Analysis of Autobody Panels

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***Abstract*—** *This paper describes experimental results for the forming limits for steel sheet DC 04 (KOHAL 200) and the deformation states in large-sized autobody panels of the Skoda, with examples of the application of these results to the analysis of an actual press forming operation. The forming-limit diagram (FLD) was determined using the in-plane stretching method. The deformation states in the large-sized autobody panels were marked on the FLD and compared with the limit strains of the sheet metal tested. Since successful forming requires the right combination of material, lubrication, sheet-blank configuration and die design, the trial-and-error method was used to determine the proper forming parameters. By analysing the strain patterns, it was possible to obtain the changes needed to convert an unfavourable stamping into a favourable one.*

***Keywords*— Autobody stampings, forming limit diagram, major- and minor-strain.**

I. INTRODUCTION

Autobody stampings can be divided generally into two main categories [1]: (i) skin panels, i.e. those that are visible on the exterior and the interior of the vehicle after all the functional and decorative trim has been added; and (ii) interior panels. These different panels are generally widely different in character, the skin panels involving large areas of metal with very low strain, the strain being largely biaxial stretching, whilst the interior panels are much more complicated in form, involving a higher level of strain in the finished part, and more complicated strain histories.

With the large flat panels dictated by modern styling requirements, uniform stretching is particularly difficult to achieve, as the direction of strain over the larger part of the panel is normally perpendicular to the direction of punch travel. This means that large areas of the panel are inevitably subjected to small strains, whereas the periphery, i.e. those areas strained over the punch and die radii, are heavily strained. When considering interior panels, the same criterion applies in some cases.

It is generally necessary with both types of stampings to produce them in large quantities at high production speed without any failure in the part. It is not sufficient to define a failed stampings as one which has a split, this term applying equally to stampings exhibiting any severe localised thinning in the metal and, for that matter, panels with excessive buckling, wrinkling and of general bad shape must also be considered failures.

Whether or not a particular sheet of metal can be formed without failure depends on the material properties, the surface condition, the blank size and shape, the lubrication, the press speed, the blank-holder pressure, the punch and die design, and many other known and unknown factors.

When the stamping tears during forming, the tear is a visible indication that the metal has been worked beyond the prevailing formability limit. A more formable material, different lubrication or re-worked tools are needed. Many stampings can be found that are close to failure but have not yet torn. During die try-out, conditions may permit critical stampings to be formed successfully, but in production the condition may be less than the optimum and breakage may then result.

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 the 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.

By measuring the strains on any given stamping and relating them to the FLD (Fig. 1), the proximity to failure can be determined for each region of the stamping [2]. Using these results, comparison can be made also between different stampings, materials, tool configurations, and the like.

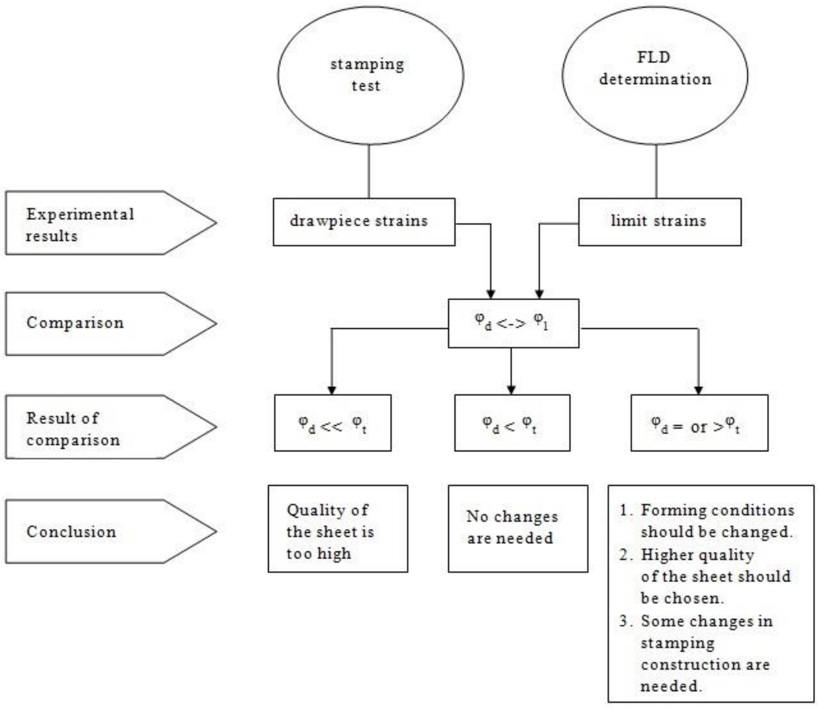

FIG. 1 SCHEME OF DEFORMATION ANALYSIS [2]

II. MATERIAL AND MECHANICAL TESTING

The test material for both mechanical testing and FLD determination, and to the auto body panels' stampings, was 0.7 mm thick deep-drawing quality aluminum-killed steel DC 04 (KOHAL 200).

Where the mechanical testing is concerned, tensile specimens of 40 mm gauge length and 20 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, i.e. $\sigma = C\varepsilon^n$. The plastic anisotropy factor r has been determined on the base of the relationship between the width strain and thickness strain in the whole range of specimen elongation according the method proposed by Welch et al. [3].

The value of the tensile parameters (Table 1) has been averaged according to:

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

Where the subscripts refer to specimen orientations of 0 °, 45 ° and 90 ° to the rolling direction.

TABLE 1
MECHANICAL PROPERTIES OF THE DC 04 (KOHAL 200) DEEP-DRAWING STEEL SHEET

	Specimen orientation relative to rolling direction			Mean value
	0°	45°	90°	
Yield stress $R_{p0.2}$ [MPa]	166	172	194	178
Ultimate strength, R_m [MPa]	348	320	340	332
Uniform elongation, A_u [%]	25.8	24.2	24.7	24.7
Strain hardening coefficient, C [MPa]	462	522	484	498
Strain hardening exponent, n	0.264	0.251	0.249	0.254
Plastic anisotropy factor, r	1.92	1.62	2.32	1.81
Surface roughness parameter, R_{tm} [μm]				4.6

III. DETERMINATION OF THE FORMING LIMIT DIAGRAM

In the present investigation, the FLD was determined using the in-plane stretching test over a flat-bottomed rigid punch (Fig. 2), according to the method proposed by Marciniak et al. [4]. This method is characterised by (i) the elimination of the friction between the specimen and tool surface, which enables the realization 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 of 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 being 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 surface of the deformed specimens 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 homogenously strained area, away from the crack. On the base of these results the FLD was obtained (Fig. 3).

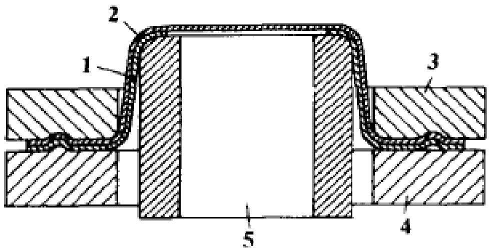

FIG. 2 SCHEME OF THE DEVICE FOR THE IN-PLANE STRETCHING TEST: (1) DRIVING BLANK; (2) SPECIMEN; (3) DIE; (4) BLANKHOLDER; (5) PUNCH

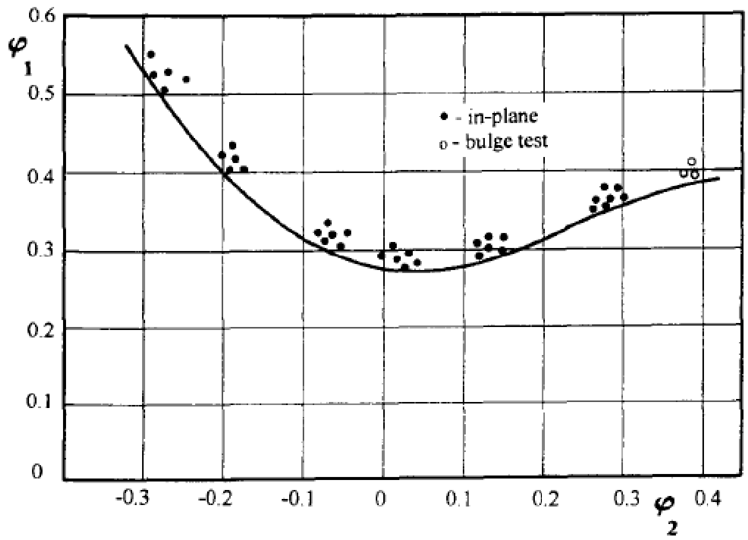

FIG. 3 FORMING-LIMIT DIAGRAM OF THE DC 04 (KOHAL 200) DEEP-DRAWING QUALITY 0.7 MM THICK STEEL SHEET

IV. THE EFFORT OF THE MATERIAL IN AUTOBODY PANELS

Several of the Skoda skin panels that created some problems in the forming process were chosen for the deformation analysis. The same kind of grid as for FLD determination was marked on the surface of the sheet blank, in the regions where the greatest strain level was expected. In the forming operations, Wedolit Z 1403 was used as a lubricant.

In the experiments, the trial-end-error method was used to achieve successful stampings, i.e. without any cracks or other defects. The strain state in the most critical areas of successful stampings were compared with the experimentally-determined limit strains of the metal (FLD).

The deformation analysis was applied to the following different stampings.

4.1 Back mudguard panel

Fig. 4 shows the deformation states in three different regions of the back mudguard panel, compared with the limit-strain curve of the sheet metal. This presentation shows that this stamping could be treated as a critical one, since the strain level in the marked regions of the stamping is very close to the limit strain. The deformation state in this stamping differs from uniaxial tension in the most strained region A, through the plane-strain state in region B, up to the biaxially stretched region C.

In the actual production forming operation some failured stampings were produced, which contained small cracks in region A and region B. Upon inspection of these stampings, visible scorings on the sheet surface were detected, which arose as a result of the accretion of metal observed on the punch surface, i.e. because of bad forming conditions.

Since the degree of strain of the material of the back mudguard panel is very close to the limit strain, the stamping regime, i.e. the blank sheet configuration, the blankholder pressure and the lubrication, has to be obeyed strictly. Additionally, for this stamping operation a good quality material is needed. Trials have shown that the value of the main mechanical parameter, i.e. the strain-hardening exponent should be in the range $n > 0.225$. The deformation state in the most strained region A is characterised by the strain ratio $\rho = \varepsilon_2 / \varepsilon_1 < 0$, which means that the value of the plastic anisotropy factor r plays a less important rule [5].

The characterisation of the surface and the frictional behaviour are important aspects in interactions between the sheet properties and the forming process [6]. To prevent the occurrence of the accretion on the punch surface, the value of the roughness-profile parameter should be in the range $R_{tm} < 10\ \mu m$.

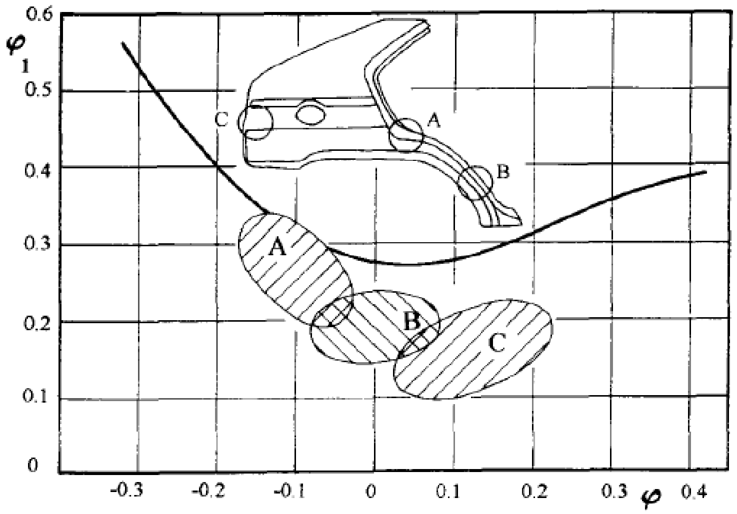

FIG. 4 DEFORMATION STATE IN THE MOST STRAINED REGIONS OF THE BACK MUDGUARD PANEL IN COMPARISON WITH THE FORMING-LIMIT CURVE OF THE STEEL SHEET TESTED

4.2. Boot-lid frame panel

When stamping the boot-lid flame panel, problems corresponding to those of the part shown in Fig. 4 could be met. Fig. 5 shows the deformation states in the characteristic regions of the part in comparison with the FLD. The deformation state in region A and region B was near to plane strain, whilst the sheet metal in region C was under biaxial stretching. Also in the case of the boot-lid flame panel, as the result of the high level of strains in region C, the stamping could be treated as critical.
It was very surprising that in the production forming operation, failed parts contained small cracks in the less strained region A. Trials have shown that there were three main reasons for this phenomenon. First, the presence of the accretion of a metal

on the punch surface, second the small clearance between the punch and die surface, and third the wrong blank sheet geometry: the flange near to the corner (region A) was too wide.

Since the degree of material strain is very close to the limit strains, the stamping regime should be obeyed strictly. When the material parameters are concerned their values should be as follows: (i) strain hardening exponent $n > 0.24$; (ii) plastic anisotropy factor $r > 1.7$; and (iii) surface roughness profile parameter $R_{tm} < 10$ µm.

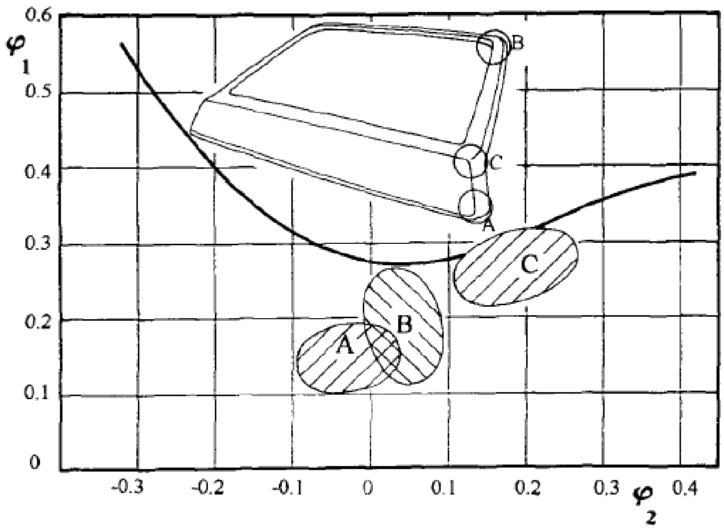

FIG. 5 DEFORMATION STATE IN THE MOST STRAINED REGIONS OF THE BOOT-LID FRAME PANEL IN COMPARISON WITH THE FORMING-LIMIT CURVE OF THE STEEL SHEET TESTED

4.3. Inner door panel

The deformation states in the most strained regions of the inner door panel were very close to each other and very close to plane strain (Fig. 6). The degree of strain of the material was slightly less than the limit strains, so that it should be expected that there would be no problems in running the stamping process. Unfortunately, in the case of is panel also several waste stampings were produced, the failured stampings containing cracks in all regions, A, B or C, this being the result of bad forming conditions: incorrect geometry of the blank sheet and insufficient lubrication. Because of the presence of the draw-beads, lubrication played an even more important rule in this stamping operation.

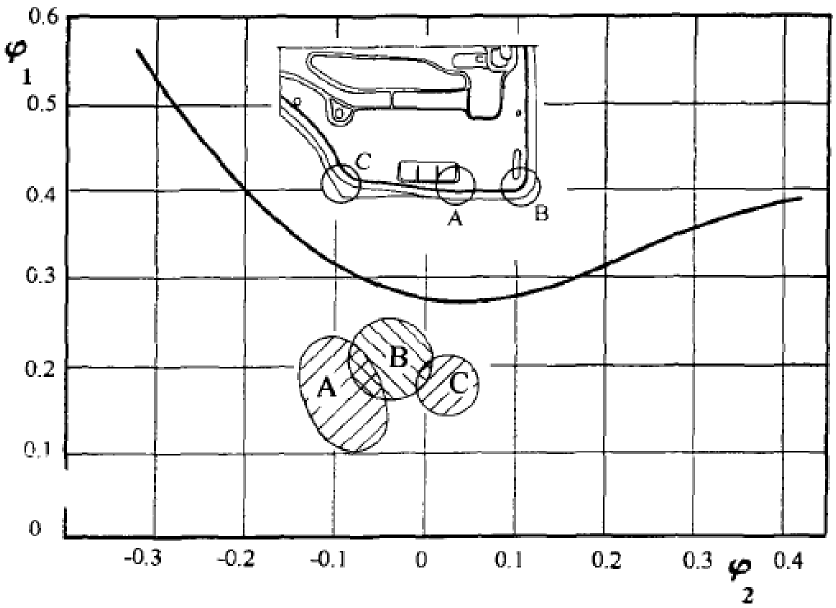

FIG. 6 DEFORMATION STATE IN THE MOST STRAINED REGIONS OF THE INNER DOOR PANEL IN COMPARISON WITH THE FORMING-LIMIT CURVE OF THE STEEL SHEET TESTED

4.4. Damper fixing panel

The damper fixing panel was made of 2 mm thick steel sheet, but since the value of the limit strain does not depend on the sheet thickness [7], the results of the strain measurements of this stamping can be compared with the FLD for the 0.7 mm thick sheet (Fig. 3).

The deformation state in the two most strained regions, A and B, was characterised by quite different strain ratio: $\rho \approx -0.5$ (uniaxial tension) in region A and $\rho \approx 1.0$ (equi-biaxial stretching) in region B (Fig. 7). The degree of strain of the material in region B was close to the limit strain, because of which failed stampings were produced in the production forming process. Sometime a wide crack was observed in region B. The main reason for the failed parts was incorrect blank-holder pressure, which resulted in wrinkling of the flange. Trials were then run to determine the optimum blank-holder pressure and, simultaneously, the most favourable geometry of the blank sheet, especially in the corner region. An improvement was made by reducing the blank width in the vicinity of the critical area of the stamping.

Additionally, it was confirmed that the blank orientation, according to the rolling direction, affected the wrinkling behaviour [8]. When the material parameters are concerned, their value should be in the same range as in the case of the stamping of Fig. 4, i.e.: (i) strain hardening exponent $n > 0.24$; and plastic anisotropy factor $r > 1.7$.

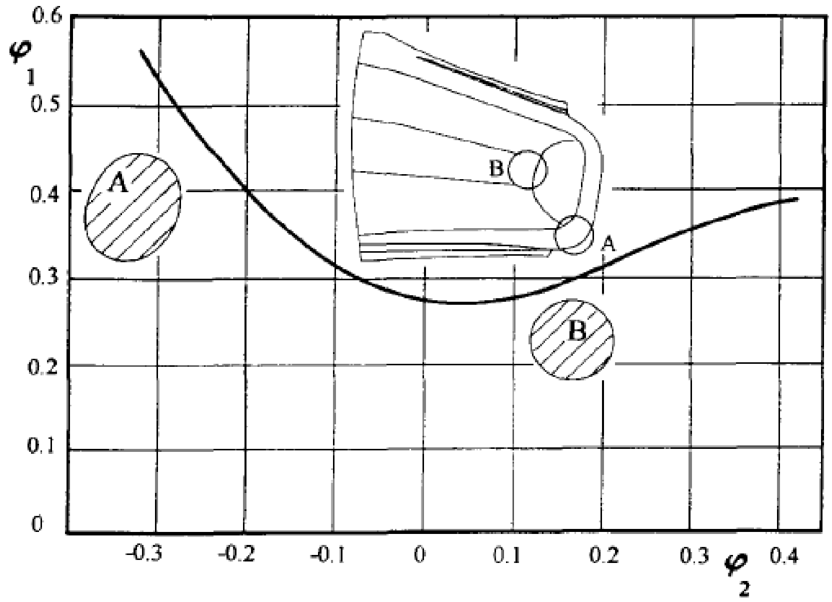

FIG. 7 DEFORMATION STATE IN THE MOST STRAINED REGIONS OF THE DAMPER FIXING PANEL IN COMPARISON WITH THE FORMING-LIMIT CURVE OF THE STEEL SHEET TESTED

4.5. Outer door panel

The degree of the material of the outer door panel was very low when compared with the FLD (Fig. 8). According to the scheme presented in Fig. 1, it could be concluded that to good-quality a material was chosen. However, in the case of autobody skin panels, the most important criterion for sheet-metal selection is the quality of the surface. Additionally when large irregular slightly bent sheet-metal parts are deep drawn, the spring-back phenomenon is very important in respect of the proper quality of the manufactured stampings. It has been emphasised [9] that the plastic anisotropy of sheet metal affects the spring-back phenomenon.

When annealed low-carbon steel sheet is pressed, unless the strain levels are particularly high in all areas of the stamping, objectionable stretch strains (Lüders lines) are produced [10]. To overcome this problem, steel sheet to be used in the more visible parts of a vehicle is temper rolled. Secondly, in the case of large shallow car-body components, the portion of stretch forming in the drawing process must be increased, such as by the application of draw-beads. The effectiveness of draw-beads depends on their size (height and width) and on their position within the tool set [11].

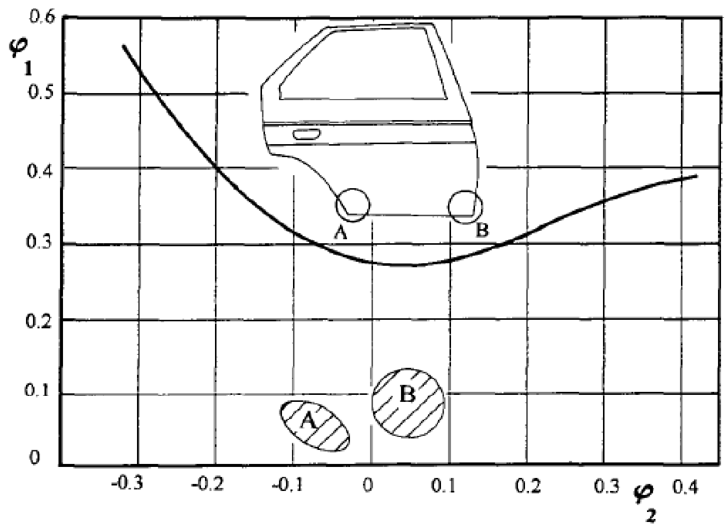

FIG. 8 DEFORMATION STATE IN THE MOST STRAINED REGIONS OF THE OUTER DOOR PANEL IN COMPARISON WITH THE FORMING-LIMIT CURVE OF THE STEEL SHEET TESTED

V. CONCLUSIONS

The forming limits of steel sheet and the deformation state of the most critical area were investigated to avoid fracture in the press forming of autobody panels. By comparing the deformation state with the forming limit, it was possible to provide some technically effective means for avoiding fracture. As a consequence of these investigations, is was shown that small changes in the technological parameters, i.e. blank sheet configuration, the blank-holder pressure, the lubrication and the tool geometry, enabled the achieving of a satisfactory reduction of breakage of the stampings, without change of the material quality.

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