Numerical and experimental study of strain distribution of trip steel sheet using hydraulic bulge test

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Abstract. This paper presents a numerical and experimental study of strain distribution in a spherical cup drawn from TRIP steel RAK 40/70 by hydraulic bulge test. The strain distribution was measured based on the data obtained by coordinate measuring machine (CMM) to identify the wall thickness and plastic anisotropy through measuring the circularity. Numerical modelling of hydraulic bulge test was performed in two types of finite element code – explicit as well as implicit. Hill's family plasticity models with a combination of two types of the hardening curves were used in the simulation model of the bulging process. The FE analysis was compared with the experimental study. The results indicate that the model is applicable to describe the wall thickness, strain distribution and bulged profile.

1. Introduction

The requirements for reducing the weight of the products and increasing their useful properties lead to the development of new types of materials, which are characterized by higher strength and better plasticity. In particular, the automotive industry in recent years has had high demands on new materials to reduce the weight of a car, increase its safety and reduce the amount of automotive fuel consumed [1, 2, 6].

For the reasons mentioned above, steel sheets with higher strength and sufficient plasticity are used for the manufacture of car bodies. These steels, which have been developed and used in recent years, include TRIP steel with the transformation-induced plasticity [2, 3, 9]. The steels are characterized by good plasticity in cold forming. During plastic deformation, the austenite is transformed into the deformation-induced martensite, which contributes to the overall hardening of the processed material. TRIP steels exhibit a uniform plastic deformation almost in the entire range of deformation. Unlike conventional low-carbon steels, these steels do not experience such significant local necking at critical places of the drawn part. Optimal design of the forming process requires being knowledgeable about the behaviour of the steels during plastic deformation at uniaxial and multi-axis stresses [4, 5, 7, 10].

Due to the requirements of the automotive industry to considerably shorten the time needed for the introduction of a new product, the use of the software enabling the simulation of the sheet-forming process has become a necessity not only for the automobile manufacturers but also for their subcontractors. On the current market, there is a wide range of such modelling software. Individual types of software are based on the method of finite elements. They use various initial parameters of used
materials and the drawing process itself. The results of each simulation process are influenced by the input data, as well as the method of their processing by particular models, and definitions of the boundary conditions of a process. To ensure that the results of this modelling software resemble the actual forming processes in the closest way possible, we must know exactly how the stress-strain relation changes in various stress-strain schemes [8, 9, 11, 13]. The results of simulation also depend on another important factor, namely a particular model of plasticity for the investigated material. The choice of the model of plasticity has a significant influence on the adequacy of the simulation results. Based on our long-term experience in the field of thin sheet processing and numerical simulation, we have concluded that numerical results are not only depend on the input parameters, but also they vary when using various software with the same input data. Hollomon (1) and Krupkowski (2) hardening models are currently one the most used for describing the strain hardening curve [12, 13, 14, 15].

\[
\bar{\sigma} = K \bar{\varepsilon}^n \tag{1}
\]

\[
\bar{\sigma} = K (\varepsilon_0 + \bar{\varepsilon}_p) \tag{2}
\]

Therefore, the paper focuses on comparing the results of simulations obtained from two programs that are, nowadays, often used for the modelling and simulation of the sheet forming processes. The results obtained from the simulation were compared with the measured results using DIC technique on ARGUS by GOM measuring system and the measuring of the true thickness of material during the hydraulic bulge test. The thickness change of an emerging spherical cup at various level of deformation was analyzed.

2. Experimental research

A thin TRIP (TRansformation-Induced Plasticity) steel sheet with the thickness of 0.75 mm labelled as RAK40/70 + Z100MBO was used for the experimental research. The sheets differ considerably from regular low-carbon steel (such as DC06), both in their chemical composition and structure. In case of low-carbon steel sheets, there is a considerable difference between total elongation and so-called uniform elongation. The uniform elongation of low-carbon steel often represents 50-60% of the total elongation [2, 16, 17, 18]. However, according to many authors [16, 19, 20] TRIP steels exhibit considerably higher percentage of the uniform elongation within the total elongation.

The tensile test was used to determine the basic mechanical properties of the material in the experiments. To compare the change in thickness calculated by various software and measured by the DIC technique using the forming analysis system ARGUS, the experimental materials underwent the bulge test on a device developed at our department. Belec Compact Port Spectrometer was used for determination of the chemical composition of the used material and the results are presented in Table 1.

| C   | Mn  | Si  | Al  | P   | Cr  | Cu  | Ni  | Ti  | Nb | Mo |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|----|
| 0.141 | 1.627 | 0.185 | 1.986 | 0.046 | 0.056 | 0.053 | 0.016 | 0.007 | 0.037 | 0.024 |

2.1. Uniaxial tensile test

The specimens for the tensile test were made from the TRIP steel according to the standard STN EN ISO 6892-1. Based on the results of this test, the basic mechanical properties of the material (yield strength, ultimate tensile strength, uniform, and total elongation), coefficient of normal anisotropy, and strain hardening exponent were estimated. Due to the anisotropy, the specimens from the used materials were taken in the direction of 0°, 45° a 90° with respect to the direction of rolling. Measured and calculated values from the tensile test are presented in Table 2.
Table 2. Mechanical properties of TRIP steel measured by the uniaxial tensile test.

| Direction $[^\circ]$ | $R_e$ [MPa] | $R_m$ [MPa] | $A_{50}$ [%] | $r_{aver.}$ | $r_m$ | $\Delta r$ | $n$ | $n_m$ | $\Delta n$ |
|----------------------|-------------|-------------|--------------|--------------|-------|-----------|-----|-------|-----------|
| 0                    | 434         | 746         | 31.2         | 0.690        |       |           |     |       | 0.293     |
| 45                   | 431         | 744         | 32.3         | 0.914        | 0.841 | 0.145     | 0.296| 0.291 | 0.010     |
| 90                   | 442         | 752         | 26.8         | 0.848        |       |           |     |       | 0.279     |

Krupkowski and Hollomon hardening models were used to extrapolating the stress-strain curves from the uniaxial tensile test, as shown in Figure 1.

![Stress-strain curves extrapolated by the hardening models.](image1)

**Figure 1.** Stress-strain curves extrapolated by the hardening models.

2.2. Hydraulic bulge test

The observed materials and their behaviour during plastic deformation in the biaxial tensile test was verified in the bulge test on the device developed at our department. The device for the bulge test is presented in Figure 2.

![Testing device for the bulge test (a) and a specimen after the bulge test (b).](image2)

**Figure 2.** Testing device for the bulge test (a) and a specimen after the bulge test (b).

The bulge test was performed on 6 specimens with the dimensions of 130 x 130 mm made from the observed material. The diameter of a hemispherical dome is 80 mm, which is the same length as the measured length $l_0 = 80$ mm during the uniaxial tensile test. The tested specimens were gradually deformed up to the height of 5.2 mm, 9.9 mm, 13.5 mm, 14.4 mm, 18.8 mm and 19.3 mm, which reflects the relative deformations of 1.1%, 4%, 7.4%, 8.4%, 14.2% a 14.8%. The specimens were labelled as T8-T3 (the specimen with a height of 5.2 mm with a relative deformation of 1.1% -- labelled T8). The
highest specimen (T3) with a height of 19.3 mm shows the deformation just before the fracture of the specimen. The diagram of the stress-strain dependence for all of the specimens is presented in Figure 3. As can be seen in Figure 3, the behaviour of the stress-strain dependence is almost identical in each specimen, i.e. only the size of the deformation varies. The device for hydraulic bulge test enables to process the measured data to estimate the stress-strain curve according to various models of the change in thickness in the area of the bulging pole (Jovane, Enikeev-Kruglov, Marciniak, Isachenkov, Atkinson). In Figure 4a), we can see the dependence of the change in thickness on the height of bulging on the spherical cup according to the authors mentioned above. Figure 4b) presents the behaviour of the stress-strain relationship according to the same authors.

![Figure 3. Stress – strain curve of TRIP steel, specimens T3–T8.](image)

a) Dependence of the change in thickness on the height of bulging. b) The stress-strain curves.

**Figure 4.** Dependence of the change in thickness and the behaviour of the stress-strain according to various authors

Figure 5 presents the stress-strain dependence during the uniaxial tensile test and the bulge test. The dependence clearly shows that the achieved deformation (in one axis) is considerably larger in the uniaxial tensile test. During the biaxial tensile test, the hardening of material proceeds differently and the intensity of the material hardening is higher than it is during the uniaxial tensile test. The stress in a time of fracture during the biaxial tensile test is higher approximately by 120 – 130 MPa.
Figure 5. Stress-strain curves from the uniaxial tensile test and the bulge test.

2.3. Measuring of Specimen Thickness by Digital Thickness Gauge

A deformation grid was electrochemically deposited on the samples prior to the hydraulic bulge test. The samples were marked in distance from 0 to 80 millimeters from the edge in 0° and 90° directions according to the direction of rolling in 10-millimeter intervals. After the biaxial tensile test, the thickness of material in the marked areas was measured using a tool with an inserted etalon. The thickness in each area was measured three times and the arithmetic mean of the obtained values was calculated. The achieved results, which were measured with the digital thickness gauge, are presented in Figures 6 and 7.

Figure 6. Material thickness in direction 0°.

Figure 7. Material thickness in direction 90°.

2.4. Measuring of Specimen Thickness by ARGUS Optical Measuring System

During bulging, the points of the deformation grid in the deformation areas shifted. The achieved values evaluated by ARGUS optical measuring system are shown in Figure 8. The calculated thicknesses show considerable asymmetry. The asymmetry is caused by numerous factors, including lower accuracy of the measuring equipment, imperfect quality of the monitored surface, quality of the deposited deformation grid, the lighting conditions during scanning of the deformation grid, and the interpolation between the grid points.
Figure 8. Values of material thickness evaluated by ARGUS.

3. Simulation of bulge test in CAE programs

The process of bulging during the bulge test was simulated using two commonly available software products designed to simulate the process of sheet drawing based on the finite element method. Two different pieces of software were used for the simulation – one with the so-called implicit solvent, and the other with the so-called explicit solvent.

A simulation model, in both cases, was created in a manner where the material was firmly fixed in the flange area to prevent it from sliding out. The entire process of deformation proceeds at the expense of material thickness in its strained areas using hydraulic fluid. In both pieces of software, the input data regarding the hardening curves (according to Hollomon and Krupkowski) were gradually entered and the models of plasticity were set according to the Hill48 and Hill90 models. The aim of the simulation was to analyse the differences caused by the changing input hardening curves and models of plasticity in the used material – TRIP steel.

The obtained results of the simulation were compared with the thinning values measured with the ARGUS optical measuring system and the actual thinning values measured manually with the digital thickness gauge.

4. Evaluation of results

The simulation was performed for each specimen, i.e. each bulging height with the proportional degree of deformation (T8-T3) was simulated. Numerical and experimental results of the deviations in thickness were compared in Figure 9. In this case, the implicit solver (software no.1) was used. Figure 10 show results from the explicit solver (software no.2). Evidently, the largest differences occurred in the area of the highest bulging; that is why we only list the thickness deviations regarding the highest bulging of the specimens.

Figure 9. Comparison of the thickness profile of the T3 specimen, the implicit solver.
Figure 10. Comparison of the thickness profile of the T3 specimen, the explicit solver.

The resulting values obtained by the simulation with various entries and measured with the ARGUS optical system were compared with the values measured manually with a digital thickness gauge. The deviations in thickness are expressed in percentage and presented in Table 3.

| Method       | Software no. 1         | Software no. 1         | Software no. 1         | Software no. 1         | ARGUS  |
|--------------|------------------------|------------------------|------------------------|------------------------|--------|
|              | Hill48-Holomon         | Hill48-Krupkowski      | Hill90-Holomon         | Hill90-Krupkowski      |        |
| Average deviation [%] | 1.40                   | 1.62                   | 1.32                   | 1.29                   | -1.65  |
| Method       | Software no. 2         | Software no. 2         | Software no. 2         | Software no. 2         | ARGUS  |
|              | Hill48-Holomon         | Hill48-Krupkowski      | Hill90-Holomon         | Hill90-Krupkowski      |        |
| Average deviation [%] | 6.28                   | 7                      | 1.63                   | 2.32                   | -1.65  |

Every deviation obtained by the simulation in the software no.1 and software no.2 is positive (calculated values of thickness are higher than the measured values). The thickness values assessed by the DIC ARGUS system are lower than the manually measured ones and that is why the percentage deviation is listed in the table as negative. The deviations in a thickness range from -1.649 % to + 7%.

5. Conclusion
The research described in the paper evaluated the plastic properties of TRIP steel during the uniaxial tensile test and bulge test. The uniaxial tensile test assessed the dependence of the actual stress and strain, and the basic strength and plastic properties of the material. During the bulge test, the material thinning on the emerged spherical cup was verified experimentally at various degrees of plastic deformation. A total of 6 degrees of deformation were selected for the experiment. The uniaxial tensile test and bulge test provided the input data for two selected pieces of sheet processing simulation software – one with the implicit solvent and one with the explicit solvent. The goal was to compare the deviations of changes in thickness that arose during the biaxial tensile test at various degrees of deformation and to calculate the changes in thickness using the selected software. For comparison, the deformations after the bulge test were also measured with the ARGUS optical
system, which assessed the change in thickness of the spherical cup after the plastic deformation. All of the measured and calculated results lead to the conclusion that the largest deviation in thickness change measured with the ARGUS optical system is -1.65% in comparison with the manually measured values of the test specimen. The calculated values of material thinning on the spherical cup after the bulge test showed that the results heavily depend on the input data and a particular model of plasticity.

In the software no.1 with the implicit solvent, smaller deviations were calculated when the hardening curve according to Hollomon and Krupkowski and the theory of plasticity Hill48 and Hill90 were used. The calculated values of thickness were smaller than the measured values and they varied by 1.29 - 1.62%. From these results, it can be concluded that the results obtained by this software using hardening curves according to Hollomon and Krupkowski and the condition of plasticity Hill90 do not vary significantly. The thickness deviation estimated by this software was, in percentage, smaller than the thickness deviation estimated by the ARGUS optical system.

The results measured and calculated in the software no.2 with the explicit solvent show that the calculated deviations in thickness change vary with regard to the input data of the hardening curve according to Hollomon and Krupkowski and the model of plasticity up to 7% deviation in thickness. The deviation was 6.2% when using the hardening curve according to Hollomon and the model of plasticity Hill48. Considerably smaller deviations in thickness were calculated by the software while using the model of plasticity Hill90 in both hardening curves. The smallest deviation in this software was estimated with regard to the hardening curve according to Hollomon. However, all the values measured in this software in all combinations exhibit larger deviations than the values in the software no.1.

**Acknowledgments**

The authors are grateful to APVV-17-0381 – Increasing the efficiency of forming and joining parts of hybrid car bodies and the project VEGA No. 1/0441/17 – Application of high-strength materials for exterior car body parts.

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