Evaluation of the stress vs strain curve using a high temperature bulge test device

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Abstract. The increasing amount of hot and warm stamping parts in the automotive industry shows that high temperature forming is critical to reach the emission goal fixed by regulation authorities, due to its contribution in reducing the vehicle’s weight. Hot stamping and warm forming take advantage of the material softening with temperature to reduce the forming forces and springback. The use of different temperature conditions also enables exploring the phase transformation occurring with in-tool quenching in hot stamping boron steels or artificial aging in heat treatable lightweight aluminum alloys. These new forming conditions require either new material characterization methods or the current methods need to be adapted to high temperature conditions. The equibiaxial expansion test allows the evaluation of the mechanical behavior of materials on a large strain range. However, the use of high temperature conditions gives rise to difficulties when using Digital Image Correlation (DIC) systems. This study analyses the possibility of using a scanner laser to obtain the stress vs. strain curve from an equibiaxial test performed with an aluminum alloy of the 6xxx series, at 150°C. The aim is to validate an experimental procedure that can be used to evaluate the stress vs. strain curve from high temperature bulge tests performed with other metallic sheets, including quenchable boron steel.

1. Introduction
The use of boron steel has been increasing in automotive applications due to its well-known potential to reduce the vehicle weight. Hot forming processes take advantage of the material softening in the austenitic state, while allowing to achieve full martensitic parts after quenching inside cooled tools. Nonetheless, the high temperature conditions required to attain the austenitic phase introduce new challenges in the evaluation of the material behavior during forming. The circular bulge test allows achieving relatively high strain values before necking, which enables the definition of the hardening law for a wide range of plastic deformation. The evaluation of the stress vs. strain curve requires recording the evolution during the test of the: pressure, pole radius of curvature and strain at the dome pole. Optical systems are now classically used to replace the more conventional measurement systems, since they enable the description of the geometry and strain distributions on the sheet surface during the test. However, the high temperature introduces technical difficulties that disable the use of Digital Image Correlation (DIC) systems for strain monitoring. Indeed, the stochastic pattern required for using this measurement method needs to withstand high temperature and large stretching without sliding nor cracks. Thus, in this work the alternative of using a scanner laser is explored. Whatever the measurement
system adopted, the stress is evaluated using the membrane theory, which relates the stress at the pole with the pressure, requiring the knowledge of the radius of curvature and sheet thickness evolutions during the test. However, the scanner laser only monitors a line on the blank surface, while DIC enables the analysis of an area. Therefore, when using the scanner laser it is necessary to use an analytical formula to estimate the thickness evolution during the test. The aim of this study is to validate an experimental procedure that can be used to evaluate the stress vs. strain curve in high temperature bulge tests performed with hot stamping materials, such as boron steels. This work presents an analysis of the analytical formulas from literature and the comparison of the stress vs. strain curves obtained in equibiaxial condition, using either DIC or the scanner laser. The study is performed for an EN AW 6061-T6 aluminum alloy at 150ºC, since this allows the analysis of the test results considering both acquisition systems.

2. Material, Experimental procedure and Analytical formulas

2.1. Material

The EN AW 6061-T6 alloy is widely used in the transport industry in structural component applications. This Al-Mg-Si series alloy show high mechanical properties, good resistance to corrosion, good formability and weldability. The chemical composition of this alloy is presented in Table 1. The T6 state indicates an artificially aged state with the formation of precipitates contributing to its hardness.

| Table 1. Chemical composition of EN AW 6061-T6 in percent composition by mass (wt.%) and thickness of the blank |
|---------|--------|--------|-------|------|--------|
| Si      | Mg     | Cu     | Fe    | Mn   | Thickness |
| 0.4-0.8 | 0.8-1.2| 0.15-0.4| <0.70 | <0.40| 0.98m   |

2.2 Experimental procedure

The setup used to perform the bulge test is presented in Figure 1. A circular blank with a diameter of 240mm is clamped into a blank holder and die, both electrically isolated and with a ceramic drawbead. The specimen is heated using the Joule’s effect. Three pairs of electrodes are used with an electrical current intensity that can go up to 6000A. Each pair is activated in a rotary manner as described in [1]. This device allows a fast heating stage, an uniform heating of the specimen, and the control of the temperature during the expansion phase. The heating is conducted in three phases: the first one is a fast heating to the testing temperature; followed by a homogenization phase; finally, the temperature of the specimen is maintained during the expansion phase of the experiment, while an argon inert gas is used to deform the specimen. A type K thermocouple, welded on the blank center by capacitive discharge, is used to control and monitor the temperature of the blank.

Figure 1. The bulge expansion device used: a) Principle of the expansion device using Joule’s effect to heat the blank, b) Rotary activation of the three pairs of electrodes.
The bulge tools are mounted in an Instron 8803 tensile test machine equipped with a load cell capacity of 500 kN. The die radius is 60 mm and its fillet radius is 5 mm, following the recommendations of the standard ISO 16808:2014 [2]. Thus, the device can be used for sheets with an initial thickness up to 1.4 mm. The strain-field at the pole is monitored with the Aramis-4M DIC system or a KEYENCE LJ-V7200 laser scanner. A TESCOM ER5000 pressure controller is used as well as a 0-70 bars pressure sensor located inside the cavity to monitor the pressure.

The scanner laser monitors only a line, which was defined passing by the center of the blank and aligned with the rolling direction. The DIC system can monitor the visible surface of the blank defined with an initial area corresponding to a radius of 60mm. The results acquired with the DIC system can be post treated using two distinct procedures. The first explores its full capability by using the information acquired for the whole visible surface of the blank, and it is referred as “Full DIC”. The second procedure is comparable to the one performed when using the scanner laser, i.e. only the information related with a line passing by the center of the blank, aligned with the rolling direction, is post treated. This post treatment procedure of the results acquired with the DIC system is referred as “DIC section”. Whatever the measurement system adopted, it is necessary to extract the height of the bulge dome during the test. When “Full DIC” procedure is used, the vertical coordinate of the highest point of the measured surface defines the height of the bulge dome, at each instant. When “DIC section” procedure is used, the coordinates of the line are fitted with a 6th degree polynomial function to describe the section. The bulge height is defined by locating the point with highest vertical position. When the scanner laser is used, the built-in function provided by the controlling software is used to evaluate the pole’s height.

2.3 Analytical formulas

Figure 2 presents a scheme of the bulge test highlighting the definition of the bulge pole’s height, \( h \); the die cavity radius, \( a \); the die fillet radius, \( df \); the blank initial thickness, \( t_0 \); the pole thickness, \( t \); and the bulge pole radius of curvature, \( \rho \).

![Figure 2. Bulge test scheme highlighting the relevant parameters (the dimensions used in the tests were: \( a=60\text{mm} \), \( df=5\text{mm} \), \( t_0=0.98\text{mm} \)).](image)

The evaluation of the stress evolution during the test is based on the classical membrane theory, which relates the stress to the thickness and radius of curvature of the blank’s apex as follows:

\[ \sigma_{membrane} = \frac{P}{2} \left( \frac{\rho}{t} + 1 \right) \]  

\[ (1) \]

where \( P \) is the pressure applied.

Several formulas have been proposed to estimate the pole thickness, resorting to the knowledge of the test geometry, material properties or final thickness (see, for example, the ones usually refereed as Kruglov method [3] or Constancy Volume Law [4]). The comparison with the results obtained with the DIC system showed that Hill formula [5]:

\[ (\text{Hill formula}) \]
\[ t = t_0 \left( \frac{1}{1 + \left( \frac{h}{a} \right)^2} \right)^2 \]  

(2)

is the one that provides the more accurate results for the EN AW 6061-T6 alloy, when using only the knowledge about the test geometry.

The thickness strain can be estimated from the thickness as follows:

\[ \varepsilon_t = \log \left( \frac{t}{t_0} \right) \]  

(3)

which enables the evaluation of the true strain, \( \varepsilon = -\varepsilon_t \), assuming an equibiaxial stress state at the pole. However, when “Full DIC” is used, the thickness strain at every instant can be evaluated using the principal strains at the pole, applying the volume constancy condition during plastic deformation\( (\varepsilon_t = - (\varepsilon_{\text{major}} + \varepsilon_{\text{minor}})) \). In this work, when using “Full DIC”, the thickness strain values evaluated considering the average major and minor strains in a region with a radius of 15mm from the pole of the bulge.

In order to compare both measurement systems on equal terms, the evolution of the radius of curvature should also be determined using only the information acquired for the pole height evolution. Hill [5] proposed the following relation:

\[ \rho_{\text{Hill}} = \frac{a^2 + h^2}{2h} \]  

(4)

which assumes a spherical shape for the cap. The radius of curvature can also be calculated using Panknin formula [6], which also assumes a spherical shape at the pole, but takes into account the fillet radius of the die’s cavity, such as:

\[ \rho_{\text{Panknin}} = \frac{(a + df)^2}{2h} + \frac{h}{2} - df \]  

(5)

These two formula are frequently used in the literature (see for example [7,8]). Koç et al. [9] shown that equation (4) consistently underestimates the radius of curvature, for the bulge test performed with an aluminum AA5754 alloy and a AISI 201 steel, both at room temperature and at 150°C. Therefore, they recommended the use of equation (5). Gutsch et al. [10] also noted that the radius of curvature estimated with equation (5) agrees well with experimental values for dome heights, normalized by the diameter of the cavity, up to \( h/a = 0.56 \). A maximum pole height of 18.7 mm was recorded for the tests with the EN AW 6061-T6 at 150°C, using the new device, which corresponds to a \( h/a \) ratio of 0.3. When using the “Full DIC” post treatment procedure, the radius of curvature at each instant is computed by fitting a sphere to the surface points.

### 3. Results analysis and discussion

Unlike the work of Bleck et al. [11], it is not possible to perform the bulge test using simultaneously the DIC system and the scanner laser with the device used in this study. Thus, two identical tests were performed. The temperature of 150°C was attained in 50 seconds. After 10 seconds of temperature homogenization, the pressure was applied at a rate of 1 bar/sec, until attaining 45 bar. Some numerical simulation studies were performed in order to determine the test conditions [1] that enable obtaining a uniform temperature in the specimen center. Both tests were stopped before the specimen failure (maximum pressure value corresponding to 85% of the pressure at fracture) to avoid damaging the measurement equipment. The DIC system requires the use of a coating to define a speckle pattern. Since it has been observed that this coating can affect the temperature distribution during the test, the coating was applied in both specimens, although it is not necessary when using the scanner laser.
3.1 Bulge test and true strain

Figure 3.a) presents the evolution of the pole height with the pressure for both tests, i.e. the two performed with the DIC system and the other with the scanner laser. This comparison is important to assure the similitude in the tests conditions, which is verified. Moreover, the results show that the testing procedure is reproducible.

![Figure 3. Expansion test performed for the EN AW6061-T6 at 150°C: a) Evolution of the pole height and b) Evolution of the true strain at the pole, vs. pressure inside the cavity.](image)

The application of equation (2) enables the estimate of the thickness evolution and, consequently, of the true strain. Figure 3.b) shows the evolution of true strain during the test, using both equation (3) and “Full DIC” averaged minor and major strains. Since the pole height vs. the pressure evolutions are similar for both tests, the resulting true strain and radius of curvature, evaluated using only the dome height are also comparable. However, the comparison with the “Full DIC” procedure indicates that the method based only in the height evolution overestimates the thickness strain by about 10%, for this material and test conditions due to an imperfect equibiaxial strain state, the major strain is about 10% larger than the minor strain.

3.2 Radius of curvature

Figure 4.a) presents the comparison between the radius of curvature vs. pressure, estimated using equation (4) and (5), labelled Hill and Panknin, respectively. Both equations are analyzed using the pole height acquired with the DIC system and the scanner laser, labelled DIC and Scanner, respectively. The figure highlights the difference between both equations, with the radius of curvature estimated using the equation proposed by Hill showing an underestimate of 10% relatively to the Panknin. The one proposed by Panknin agrees well with “Full DIC” procedure, particularly in the interval between 10 and 45 bars.

The results shown in Figure 4 are in agreement with the ones previously mentioned from the literature. This confirms that the improved knowledge about the test boundary conditions leads to a higher estimate of the radius of curvature. When comparing the results from both measurement systems, there is a higher difference in the interval between 0 and 5 bars, for which the curvature is smaller. Nevertheless, the detail in Figure 4.a) shows the convergent evolution to identical results with the increase of the pressure. The resulting true stress vs. plastic strain evolutions are presented in Figure 4.b). The plastic strain was evaluated taking into account the correction of the elastic strain. When considering the results based on the evolution of the line aligned with the rolling direction, the only variable that is being evaluated using different equations is the radius of curvature at the pole. Therefore, a trend similar to the one of Figure 4.a) is observed, i.e. the stress is underestimated by a factor of 10% when using equation (4), compared with the results obtained with equation (5). When comparing the
evolution obtained with equation (5) with the one generated by the “Full DIC” procedure, it is possible to confirm the influence of the difference in true strain showed in Figure 4. b). Note that “Full DIC” procedure leads not only to a lower true strain value and, consequently, to a higher value for the thickness. Thus, equation (1) will lead also to a lower value for the stress at the pole.

3.3 Comparison between tensile and bulge tests

Figure 5 shows the stress vs. strain curve obtained with the uniaxial tensile test, performed with the same material [12]. In this case, the results are shown until the instant corresponding to the maximum tensile force. The comparison with the results obtained from the bulge test show that the material presents a similar value for the yield stress of 230 MPa. As expected, the maximum strain attained in the bulge stress is larger, although the test was not performed until the specimen failure.

Figure 5 also highlights that the hardening slope is different for the bulge test and the uniaxial tensile test, with the expansion test showing a higher hardening with the increase of strain than the tensile test. Although there are no tensile test results available for different strain rates at 150ºC, the results for 200ºC show that this alloys presents a positive strain rate sensitivity [13]. The results shown in Figure 5 were obtained for an initial strain rate of $\dot{\varepsilon} = 2 \times 10^{-3}$ s$^{-1}$, for the uniaxial tensile test, while for the bulge test the initial strain rate is $4 \times 10^{-3}$ s$^{-1}$. Moreover, the strain rate tends to increase during the bulge test, based
on the work of Banabic et al. [15] several authors [14], [16], [17] managed to control the strain-rate. Thus, the positive strain-rate sensitivity at 150°C seems to be consistent with the work of Simões et al. [13] on the EN AW 6061-T6 alloy at 200°C and can explain the different hardening slope. The “Full DIC” results are in agreement with the results obtained with equations (2) and (5). Finally, the oscillations observed on the stress vs. strain curves can be related with deviations from the linear increase of the pressure, which can also lead to changes in the strain rate.

4. Conclusion
This work presents a comparison of two measurement systems: DIC and scanner laser, in the analysis of the results from bulge tests in warm conditions. A new device was used and the tests performed at 150°C were proven to be repeatable. The evolution of the radius of curvature was estimated using only the pole height and two classical analytical equations and compared with a DIC surface measurement. The results show that the scanner laser can be an alternative to overcome the difficulties associated with the use of DIC systems at high temperatures. Nevertheless, the analysis of the results also indicate that an improved knowledge is required regarding the strain rate evolution during the test. This will contribute to an improved analysis of the mechanical behavior of metallic materials at high temperatures, in particular the study of bulge tests performed with boron steel, like Usibor, and potentially other materials.

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