Research article

Numerical investigation of the effect of punch corner radius and die shoulder radius on the flange earrings for AA1050 and AA1100 aluminum alloys in cylindrical deep drawing process

K. Bouchaala a, b, *, M.F. Ghanameh a, c, M. Faqir a, M. Mada b, E. Essadiqi a

a Université International de Rabat, AERO School of Engineering, LERMA Lab, Roccade Rabat-Sale, 11 100 Sala el Jadida, Morocco
b Université Mohamad V, Ecole Mohammadia d’Ingénieurs, ITACS Lab, Agdal-Rabat, Morocco
c Faculty of Mechanical and Electrical Engineering, Damascus University, Damascus, Syria

ARTICLE INFO

Keywords:
Aluminum alloys
Anisotropy
Cylindrical deep drawing
Die shoulder radius
Earring
Finite element method
Punch nose radius

ABSTRACT

In aeronautic sectors, lightweight materials are very demanded in order to reduce fuel consumption. Therefore, thinning drawn cups are very recommended. Reduction of thickness led to many geometrical and physical failures that damage the final product. Since most lightweight materials had a high level of anisotropic, the presence of earrings is one of the most significant failures faced in the deep drawing process. Many functions were developed in order to control these undesirable earrings in sheet metal parts. In this paper, a simulation of a 3D cylindrical deep drawing model for AA1050 and AA1100 aluminum alloys using ABAQUS finite element software was achieved. Prediction of earing phenomenon in deep drawing process was carried out. Moreover, the impact of punch corner radius and die shoulder radius on flange earrings was analyzed and a reduction of the percentage of earing heights was investigated.

1. Introduction

The requests for materials that had lightweight and high mechanical properties increases. Aluminum and aluminum alloys are widely used in engineering design because of their good corrosion resistance, ductility at low temperatures and high strength [1]. The product cost reduction and the quick technological development in aluminum and aluminum alloys sheet forming have become key factors in many manufacturing areas [2].

Deep drawing is one of the simple, typical and popular forming techniques as shown in Figure 1.

It consists of the punch pressure on flat blanks [3]. As the material is stamped into the die by the punch, it flows into a 3D shape between the surfaces of the punch and the die. The flange of the blank is clamped by the blank holder force against the die to obtain the required drawn product [4].

Shapes made from the deep drawing process have several attractive qualities: adequate strength, lightweight parts, and a broad range of possible dimensions, from the small parts in electronics to the large parts of airplane assemblies. Whatever cost is the most pertinent of these qualities, the most efficient design should also reach the lowest possible cost.

Several studies have been realized using diverse technologies involving experimental, analytical and computational methods in order to have a deeper understanding of forming processes.

Among them, computational methods, especially the finite element method (FEM), have become a powerful tool during recent decades. The most significant mode of FEM in metal forming processes is the numerical simulation or computer aided engineering (CAE) [4], it reduced the time and product development costs. It required also the efficient use of simulation techniques from the earliest stage of product development, to give feedback from each step to make the necessary corrections and improvement when it takes the least cost [5].

Besides time and cost, the deep drawing process is influenced by geometrical and material parameters. The effect of geometrical parameters such as blank thickness, punch nose radius, die shoulder radius and tooling dimensions is crucial. Moreover, material properties like elasticity, plasticity and anisotropy have as much influence as the geometry parameters. The incorrect definition of these parameters explains the defective results like wrinkling, tearing, earring and spring-back [6]. The impact of these parameters on formability has been highlighted by many researchers. Zein et al. [7] predicted thinning and thickness distribution of the blank with the die design parameters with finite element method.
for the deep drawing process. Bouchala et al. emphasized the influence of friction coefficient on a cylindrical deep drawing in three different regions for AA2090 [8] [9] and AA2198 [10] [11] aluminum lithium alloys using finite element studies. Reddy et al. [12] applied an experimental analysis to analyze the influence of geometrical parameters on thickness variation during the sheet forming process. Bouchala et al. [13] investigated the effect of anisotropic and isotropic yield functions on the thickness distribution on a finite element deep drawing model of AA2090 Al-Li alloy.

Anisotropy has a fundamental role, within sheet metal forming, and its description is important for the accurate design of manufacturing processes. Anisotropy in the formability of sheet metal is a combination of thermo-mechanical processing history which led to an initial anisotropy with the plastic deformation during the forming operation [14]. The modeling and the implementation of plastic anisotropy in finite element (FE) codes may be complex. Many phenomenological yield functions have been proposed to predict the anisotropic plastic behavior of the sheet metal forming (e.g. Hill [15], Barlat et al. [16, 17], Bron and Besson [18]). Das et al. [19] predicted earrings problem in cylindrical deep drawing cups using finite element and modeled by HYPERWORKS-6.10 software. Pawan [20] developed numerically a modification of the initial blank shape to reduce the percentage of earring height with the help of ABAQUS software.

In this paper, finite element analysis was used to predict earring heights of two aluminum alloys: AA1050 and AA1100, with the help of ABAQUS software. As a first step, a comparison between the presented finite element model and the published experimental results was carried out, after the good agreement obtained between the two results, this numerical model was developed in order to illustrate sheet metal anisotropy at macroscopical level by the appearance of earrings, furthermore to investigate the impacts of die shoulder radius and punch nose radius on earrings heights and to minimize the percentage of these earrings during deep drawing process, which was not discussed in previous researches.

2. Constitutive equations

2.1. Plastic anisotropy

Lankford parameter also called Lankford value, \( r \)-value, plastic strain ratio or anisotropy coefficient is the parameter which measures the variation of the plastic behavior with direction [21], in order to calculate this coefficient samples at 0°, 45° and 90° with respect to the rolling direction. The material must be machined and tested under uniaxial tensile test. To express the \( r \)-value, the true width strain \( \varepsilon_w \) and the true thickness strain \( \varepsilon_t \) have to be evaluated in uniform elongation area, beyond the material elastic limit, in general, 20% elongation:

\[
r = \frac{\varepsilon_w}{\varepsilon_t}
\]  

Using the notations from the equation can be written as:

\[
r = \frac{\ln \frac{w}{w_0}}{\ln \frac{t}{t_0}}
\]  

Where \( w \) is the final width and \( w_0 \) is the initial width, while \( t \) is the final thickness and \( t_0 \) is the initial thickness. If the material has an isotropic behavior, the thickness strains have the same value of the widths and their ratio in this case is one [20], this coefficient is much less sensitive to errors measurement than errors in thickness and width measurements [22], which led to express it from the measurement of length and width using the constant volume assumption as follows:

![Figure 1. 3D Schematic illustration of deep drawing process.](image1)

![Table 1. Tool dimensions.](image2)

| Parameters         | Dimension in mm |
|--------------------|----------------|
| Punch radius       | 30             |
| Punch nose radius  | 6              |
| Blank size radius  | 51             |
| Blank thickness    | 1              |
| Die radius         | 16.5           |
| Die shoulder radius| 5              |

![Figure 2. 2D Geometry of cup drawing assembly.](image3)
The r value frequently differs with the direction in the sheet. The anisotropic yield stress ratios $R_{11}, R_{22}, R_{33}, R_{12}, R_{13}$ and $R_{23}$ are ascribed as user input in ABAQUS software [23], these parameters are determined as:

\[
R_{11} = R_{13} = R_{23} = 1
\]

\[
R_{13} = \sqrt{\frac{r_x(r_x + 1)}{r_x + r_y}}
\]

\[
R_{23} = \sqrt{\frac{r_x(r_x + 1)}{r_x(r_y + 1)}}
\]

The r value frequently differs with the direction in the sheet. The anisotropic yield stress ratios $R_{11}, R_{22}, R_{33}, R_{12}, R_{13}$ and $R_{23}$ are ascribed as user input in ABAQUS software [23], these parameters are determined as:

\[
R_{11} = R_{13} = R_{23} = 1
\]

\[
R_{13} = \sqrt{\frac{r_x(r_x + 1)}{r_x + r_y}}
\]

\[
R_{23} = \sqrt{\frac{r_x(r_x + 1)}{r_x(r_y + 1)}}
\]

The average of the Lankford parameter in 3 directions $r_x$ in 0°, $r_{45}$ in 45° and $r_y$ in 90° called the normal anisotropy and it highly affects the performance of deep drawing. As much this coefficient attends higher values as much the material has optimum formability [13]. The coefficient of normal anisotropy is expressed by:

\[
R = \frac{r_x + 2^r45 + r_y}{4}
\]

2.2. Planar anisotropy

The planar anisotropy measures the variation of r-value with rolling direction and is defined as:

\[
\Delta R = \frac{r_x - 2^r45 + r_y}{2}
\]

In deep drawing application planar anisotropy and normal anisotropy are very important on the design parameter, while the normal anisotropy determines the average cup height of the extra deep draw, the planar anisotropy defines the extent of earrings. For a better formed sheet, a combination of a high R value and a low ∆R value is necessary [24]. Ears are formed at the flange of the cup using extra deep drawing. The direction of the flange earing and the extent have been determined by the sign of the ∆R [25]. The impact of planar anisotropy has been known and interpreted for a long time qualitatively, in relation to the angular evolution of the anisotropy coefficient, if $r_x = r_{45} = r_y$ and $\Delta R = 0$, earing does not emerge, else if $r_x = r_y$ and $\Delta R < 0$, four ears with the same intensity are formed at 45° to the rolling direction else if $r_x < r_y$ and $\Delta R > 0$, four ears are formed at 0° and at 90°, the intensity of the ears is greater at 90°, otherwise for $\Delta R = 0, r_x < r_y$, two horns are formed at 90° and four at 45° [26].

2.3. Hill 48 yield criterion

A yield criterion is a mathematical function of the stress states to determine the limit of elasticity in a material and the onset of plastic deformation under any possible combination of stresses.

HILL 48 criterion was used in the present numerical simulation to describe the conditions for yielding due to its reduced complexity and less simulation time requirement. In this criterion the equivalent stress is determined as [27]:

\[
\sigma = \sqrt{H(\sigma_{xx}-\sigma_y)^2+F(\sigma_{yy}-\sigma_z)^2+G(\sigma_{zz}-\sigma_x)^2+2L\sigma_{xy}^2+2M\sigma_{yz}^2+2N\sigma_{xz}^2}
\]

\[
\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{yz}, \sigma_{xz}
\]

and $\sigma_{xy}$ are the components of stress tensor and $H, F, G, L, M$ and $N$ are constants specific to the anisotropy state of the material which can be expressed as:

\[
H = \frac{1}{2} \left( \frac{1}{R_{11}} + \frac{1}{R_{22}} - \frac{1}{R_{33}} \right)
\]

\[
F = \frac{1}{2} \left( \frac{1}{R_{22}} + \frac{1}{R_{33}} - \frac{1}{R_{11}} \right)
\]

\[
G = \frac{1}{2} \left( \frac{1}{R_{11}} + \frac{1}{R_{33}} - \frac{1}{R_{22}} \right)
\]

\[
L = \frac{3}{R_{33}}
\]

Table 2. Material data for AA1050 and AA1100 used in this work.

| Material      | AA1050 [26] | AA1100 [28] |
|---------------|-------------|-------------|
| Density (kg/m³) | 2700        | 2710        |
| Strength coefficient (k) (Mpa) | 149         | 99          |
| Strain hardening exponent (c) | 0.287       | 0.19        |
| Young Modulus (E) (Gpa) | 69          | 69.8        |
| Yield stress (Y.S) (Mpa) | -           | 47.9        |
| $\epsilon_0$ | 0.0035      | -           |
| Poissons ratio | 0.33        | 0.33        |
| $\sigma_0$ | 0.8         | 0.649       |
| $\sigma_0$ | 0.55        | 0.667       |
| $\sigma_0$ | 0.89        | 0.611       |
| Hardening laws | 149 (0.0035 + $\epsilon$)² | 47.9 + 99 * $\epsilon$³ |

Figure 3. Finite Element model of Deep Drawing Cup.
punch as a boundary constraint while the die was fixed in all directions. Due to the orthotropic material properties of the aluminum sheet, the numerical analysis of the deep-drawing was processed by using only one quarter section of the 3D numerical model with the corresponding symmetry boundary conditions to reduce the computational time.

### Material properties

Two different aluminum alloys AA1050 and AA1100 have been selected for this work, in order to accomplish a detailed comparison and to enhance the final formed sheet metal. The mechanical properties and the hardening laws that characterized the behavior of both alloys are expressed in Table 2.

### Meshing

The die, the punch and the holder are stiffer than the rest of the model therefore deformation can be considered negligible and tools were modelled as a rigid form whose motion was governed by the motion of a single node, known as the rigid body reference node and were meshed with (R3D4) surface elements. A generation of 385 elements have been done on the die, 300 elements on the holder and 397 elements on the punch as shown in Figure 4.

The blank which considered a deformable part, was modelled using reduced integration shell element (S4R) [29], about 900 elements have been generated as illustrated in Figure 5. Reduced integration elements are often preferred in industrial applications due to their time efficiency and good overall accuracy.

### Result and discussion

The final cup product obtained by numerical simulation using the extra deep drawing process was highlighted in Figure 6, where the difference between the isotropic and anisotropic behavior is observed on the flange of the cups. In the isotropic model the flange has a constant height while different height on the flange of the cup called ears appears on the anisotropic case.

#### Validation of the model

A difference between height and low points were found concerning the two alloys AA1050 and AA1100, this dissimilarity in the earrings
Figure 6. Numerical simulation of extra deep drawing (a) isotropic behavior, anisotropic behavior: (b) for AA1100 (c) for AA1050.

Figure 7. Comparison of two different distributions of planar anisotropy coefficient (a) AA 1100, (b) AA 1050.

Figure 8. The profile of the earrings height difference with the rolling angle from the numerical simulation a) AA 1050, b) AA 1100.
shapes between the two alloys are conditioned by planar anisotropy parameter $\Delta R$ as described in Figure 7.

For the AA1100 aluminum alloy, the value obtained by calculating the planar anisotropy is $\Delta R = 0.295$, which is a positive value as presented in Figure 7a. In this case, according to literature the four earrings should appear with the same size formed in the 45° direction. The finite element analysis shows exactly the same results with literature as presented in Figure 7b.

While for AA1050 aluminum alloy, the planar anisotropy found is $\Delta R = -0.037$ which is a negative value as presented in Figure 7b. In this case two earrings should appear at the directions of 0° (or 360°) and 90° respectively. The earring along the direction of 90° is closely larger than those along the direction of 0°, which correspond to the obtained numerical results as described in Figure 8b.

After the much between the theory and the numerical model at the level of earring shape based on the planar anisotropy results. A comparison between the presented finite element model against the experimental results of S. Msolli et al. [30] has been used to validate the numerical model as shown in Figure 8.

S. Msolli et al. provided the experimental cup profile of AA1050 aluminum alloy as detailed in Ref [30]. Figure 9 shows the variation of cup height with rolling angle. Moreover, four ears appear along the angle of rolling direction (ϕ°), two heights ears are recorded at (90° and 270°) and two smalls at (0° or 360° and 180°) respectively. A good agreement observed between the simulated cup earing profile and the experimental results.

4.2. The impact of punch corner radius and die shoulder radius on the flange earrings

Figure 10 presents the percentage of earrings heights for different values of die shoulder radius (rd) and punch nose radius (rp). For AA1100 Aluminum alloy, All the waves had the same height in different rolling angles due to the planar anisotropy as explained before. For the smallest value of rp which is 1mm the reduction of earring height was 3% from 3mm to 8mm of rd. This reduction became lower as much the punch shoulder radius increased; 2.5% when rp is between 2mm and 4mm; 2.3%,2.2% and 2% when rp is 5mm, 6mm and 8mm respectively. Therefore, according to these results, the best combination in this case is a punch nose radius of 1mm and a die shoulder radius of 8mm.

Concerning AA1050 Aluminum alloy, the waves did not have the same heights at different rolling angles. The higher ears appeared at 90° and 270° are really impacted by the die shoulder radius compared to the lower ears at 0°, 180° and 360°.

For the higher waves at 90° and 270°, the reduction was more than 5% from a rd = 2mm to rd = 6mm, while the punch nose radius did not demonstrate a significant effect on the percentage reduction of the higher ears. Nevertheless, the impact of the punch nose radius is seen in the lower ears (0°, 180° and 360°); as much as rp increased the reduction percentage resulting shrunk at these angles till it hits zero when rp = 8mm. At the smallest value of punch nose radius (rp = 1mm) the reduction of earrings heights was 0.8% from rd = 2mm to rd = 6mm, this reduction was increased to 1.4% when rp = 2mm and slightly decreased when rp was above 2mm. The best combination between the reduction of earrings percentage in the different rolling angles was a punch nose radius of 2mm and a die shoulder radius of 9 mm.

In the deep drawing process, the material located at the flange is stretched radially into a certain direction and pressed circumferentially perpendicular to this direction. The element in contact with the blank-holder is strongly pinched against the die, as it conveys the entire holding force. Die shoulder radius and punch nose radius play a major role in force distribution and material flow during the sheet metal deep drawing process, thus the earring outcome, it is noteworthy that die shoulder radius for deep drawing manufacturing should be sufficient to allow a smooth metal flow which reduces earring height.

5. Conclusion

In this study AA1050 and A1100 aluminum alloys have been studied using ABAQUS/EXPLICIT finite element software in order to predict the earring phenomenon. As a first step a validation of the 3D model at the theoretical level (planar anisotropy) and experimental level (S.Msoll et al. [30]) was carried out. A development of the numerical model was done in order to investigate the impact of punch nose radius and die shoulder radius on the earring heights. Relying on the results, it can be concluded that the planar anisotropy parameter $\Delta R$ influences the enlarging, shape, and size of earrings. Furthermore, the die shoulder radius and punch nose radius effect on the height of ears, 3% and 5% of earrings heights reduction were seen for AA1100 and AA1050.
Figure 10. Comparison of percentage earrings for different punch corner radius and die shoulder radius for AA1050 and AA1100.
respectively. Consequently, exploiting the known effect of all these parameters leads to improve the optimization of model production.

Declarations

Author contribution statement

K. Bouchaala: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

M.F. Ghanameh, M. Faqir & M. Mada: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data.

E. Essadiqi: Contributed reagents, materials, analysis tools or data.

Funding statement

This work was supported by the Centre National de Recherche Scientifique et Technique (CNRST) of Rabat, Morocco.

Data availability statement

The datasets of AA1050 Aluminum alloy analyzed during the current study are available in the Thesis named “caractérisation experimentale et modélisation de la déformation plastique des toles métalliques”, while the datasets of AA1100 Aluminum alloy used during the current study are available in the Journal paper “A theoretical, numerical, and experimental investigation of plastic wrinkling of circular two-layer sheet metal in the deep drawing”.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] MacKenzie, George E. Totten, D. Scott, Handbook of Aluminum, Physical Metallurgy and Processes, Marcel Dekker Inc, New York, 2003.
[2] K. Zheng, D.J. Politis, L. Wang, J. Lin, “A review on forming techniques for manufacturing lightweight complex-shaped aluminium panel components, Int. J. Lightweight Mater. Manufacture (2018).
[3] P. Vukota Boljanovic, SHEET METAL FORMING PROCESSES AND DIE DESIGN, Industrial Press Inc, New York, 2004.
[4] Cyril Donaldson, H LeCain George, V.C. Gold, Joyjeet Ghose, Tool Design, Special Indian Edition, 2012.
[5] Karl Roll, Simulation of sheet metal forming- necessary deve, LS-DYNA Awenderforum A (1) (2008) 59–68.
[6] A.S. Talatkar, L. Babu, M. Chinnapandi, “Deep drawing process at the elevated temperature: a critical review and future research directions, CIRP, J. Manufactur. Sci. Technol. (2019).
[7] H. Zein, M Abd-Rabou M El-Sherbiny, M. El Shazly, Effect of die design parameters on thinning of sheet metal in the deep drawing process, Am. J. Mech. Eng. 1 (2013) 20–25.
[8] K. Bouchaala, M. Faqir, M. Ghanameh, M. Mada, E. Essadiqi, Investigation of friction behavior of AA2090 Al-Li alloy in cylindrical deep drawing sheet metal using finite element, Int. J. Mech. Prod. Eng. Res. Dev. (2019).
[9] Kenza Bouchaala, Mohammad Fathi Ghanameh, Mustapha Faqir, Mohammad Mada, Elhachmi Essadiqi3, Prediction of the impact of friction’s coefficient in cylindrical deep drawing for AA2090 Al-Li alloy using FEM and Taguchi approach, in: IOP Conference Series: Materials Science and Engineering, BULTRANS19, 2019.
[10] Kenza Bouchaala, Mustapha Faqir, Mohammad Fathi Ghanameh, Mohammad Mada, El Hachmi Essadiqi, Investigation of Contact Impact in deep drawing for AA2198 Al-Li sheet using ABAQUS/Explicit, Adv. Intelligent Syst. Computing (2020).
[11] Kenza Bouchaala, Mohammad Fathi Ghanameh, Mustapha Faqir, Mohammad Mada, Elhachmi Essadiqi, Evaluation of the effect of contact and friction on deep drawing formability analysis for lightweight aluminum lithium alloy using cylindrical cup, Procedia Manufacturing 46 (2020) 623–629.
[12] A.C.S. Reddy, S. Rajesham, P.R. Reddy, T.P. Kumar, J. Goverdhan, An experimental study on effect of process parameters in deep draw using Taguchi technique, Int. J. Eng. Sci. Technol. 7 (1) (2015) 21–32.
[13] Kenza Bouchaala, Mohammad Fathi Ghanameh, Essadiqi El Hachmi, Mustapha Faqir, Mohammad Meziane, Mohammed Mada, Modeling of anisotropy influence on thickness distribution of deep drawing sheet, Advanced mechanical and electrical engineering (AMEE), in: ACM International Conference Proceeding Series, 2018, pp. 142–146.
[14] D. Banadic, Sheet Metal Forming Processes: Constitutive Modelling and Numerical Simulation, Springer Science & business Media, 2010.
[15] Hill, A theory of the yielding and plastic flow of anisotropic metals, Proc. Roy. Soc. Lond. 193 (1948) 281–297.
[16] F. Barlat, J.C. Brem, J.W. Yoon, K. Chung, R.E. Dick, D.J. Lege, F. Pourboghrat, S.H. Choi, E. Chu, Plane stress yield function for aluminum alloy sheets-part 1: theory, Int. J. Plast. 19 (2003) 1297–1319.
[17] F. Barlat, H. Aretz, J.W. Yoon, M.E. Karahin, J.C. Brem, R.E. Dick, Linear transformation based anisotropic yield functions, Int. J. Plast. 21 (2005) 1009–1039.
[18] F. Besson, Bron, J. A yield function for anisotropic materials. Application to aluminium alloys, Int. J. Plast. 20 (2004) 937–963.
[19] P. Das, S.K. Panda, D.K. Pratihar, Modification of initial blank shape to minimize earing in deep drawing process, Adv. Mater. Manuf. Char. 3 (2013).
[20] Pawan S. Nagda, Purnak S. Bhat, Mit K. Shah, Finite element simulation of deep drawing process to minimize earing, Int. J. Mech. Mechatron. Eng. 11 (2) (2017) 413–416.
[21] W.T. Lankford, S.C. Snyder, J.A. Bauscher, New criteria for predicting the press performance of deep drawing sheets, Trans.ASM 42 (1950) 1197–1205.
[22] R. Gedney, Sheet metal formability, Adv. Mater. Process. (2002) 33–36.
[23] D.T. Nguyen, D.K. Dinh, H.M. Nguyen, T.L. Banh, Y.S. Kim, Formability improvement and blank shape definition for deep drawing of cylindrical cup with complex curve profile from SPCC sheets using FEM, J. Cent. South Univ 21 (2014) 27–34.
[24] S. Bruchi, A. Ghiotti, Advanced Forming Technologies, Comprehensive Materials Processing, 2014.
[25] Y.P. Hu, Numerical study of the flange earring of deep drawing sheets with stronger anisotropy, Int. J. Mech. Sci. 43 (2001) 279–296.
[26] M. Teaca, Caractérisation experimentale et modélisation de la déformation plastique des toles métalliques, Université Paul Verlaine-Metz, 2009.
[27] H.R, A theory of the yielding and plastic flow of anisotropic metals, Proc. Roy. Soc. Lond. 193 (1944) 281–297.
[28] M.R. Morovvati, B. Mollaei-Dariani, M.H. Asadian-Ardakani, A theoretical,numerical,and experimental investigation of plastic wrinkling of circular two-layer sheet metal in the deep drawing, J. Mater. Process. Technol. 210 (2010) 1738–1747.
[29] Abaqus Analysis User’s Guide Manual, Elements 2014 vol. IV.
[30] S. Mosili, H. Badreddine, C. Labergere, M. Martin, G. Robin, M. Jrad, K. Saanouni, F. Chouquet, Experimental characterization and numerical prediction of ductile damage in forming of AA1050-O sheets, Int. J. Mech. Sci. (29 January 2015).