Characterization of wrinkling limit for metallic sheet

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Abstract

Nowadays the industry have seen the growing interest for materials with better properties available at lower cost. Thus the material formability limits characterization become very relevant in the stamping community. This evaluates the possibility of characterizing the wrinkling limit through experimental tests and numerical simulation.

The characterization of the wrinkling limit of the material was performed by Instability tests on rectangular sheet specimens. The test specimen is compressed till instability is achieved, with the consequent wrinkling in the specimen. The principal strains pair achieved at the instability instant, is called the critical strains pair, which was used to trace the wrinkling limit.

The wrinkling limits were characterized for the AA1050-O aluminium sheet with 1, 2, 3 and 4 mm of thicknesses. Several tests were carried considering different slenderness ratios, each ratio gives a critical strains pair, this way the obtained wrinkling limit was accurate. With the increase of the slenderness ratio instability is achieved for lower material deformation.

The characterized wrinkling limits were then successfully validated by Swift tests, thus confirming the possibility of characterizing the wrinkling limit through the proposed experimental and numerical instability tests.

It should be noted, that the sheet thickness has a significant influence on the wrinkling limit, due to the fact that the results for higher thicknesses instability occurs at larger deformations.

Keywords: Sheet Metal, Formability, Wrinkling, Instability, Experimentation, Numerical Analysis.

1. Introduction

Workability sets the limits on the amount of deformation that can be applied to sheet metal blanks without failure, and is commonly evaluated by means of forming limit diagrams, built upon the principal strain space. The forming limit diagrams provide the failure locus at which plastic instability occurs and localized necking develops (forming limit curve - FLC), the failure loci at the onset of fracture by tension (fracture forming limit - FFL) and by in-plane shear (shear fracture forming limit - SFFL) and the wrinkling limit. Marciniak [1] was the first researcher to incorporate these formability limits in the principal strain space.

The formability limit by necking is characterized by the forming limit curve, FLC, that indicates the amount of deformation where aesthetic problems and incipient fracture derived from thinning are likely to develop in sheet metal parts. This curve is determined through experimental formability tests, in which the specimens are marked with a circle-grid in the blank before the forming operation via etching or imprinting. After the forming operation, the circles turn into ellipses, there after being able to calculate the major and minor in-plane strains, using equations 1 and 2, respectively, which are computed using both major, \(a\) and minor, \(b\) ellipse axis, as well as the undeformed circle diameter, \(d\).

\[
\varepsilon_1 = \ln \left[ \frac{a}{d} \right] \quad \varepsilon_2 = \ln \left[ \frac{b}{d} \right]
\]  

(1), (2)
For fracture the determination of both FFL and SFFL can be performed by means of double notched test loaded in tension, torsion and in-plane shear specimens, as well as establishing a connection between critical damage at the onset of cracking and fracture toughness by opening modes I [3], and II [4].

The wrinkling phenomena is transverse to multiple sheet metal forming processes, especially in stamping operations, like those in figure 1 (a). Thus, the attempt to predict the onset of wrinkling has required the attention of several investigators.

![Figure 1 - (a) Wrinkling representation on the flange area; (b) region dominated by compression tangential stresses [2].](image)

Figure 1 shows two representations of wrinkling in the flange area of a cylindrical cup. By observation of figure 1 (a), it appears that the wrinkling is a visual defect in the workpiece. Figure 1 (b) shows the representation of the radial stresses ($\sigma_r$), which are prevalent in the wall area of the cylindrical cup during the stamping operation, being these mainly of tension. In the same figure, compressive tangential stresses ($\sigma_\theta$) prevail in the flange area of the cylindrical cup, resulting in a decrease of the section area [2].

The formability limit by wrinkling is located in the lower left-hand part of the second quadrant of the principal strains space and is influenced by the material's mechanical properties, the geometry of the sheet metal part, the contact conditions imparted by tooling and the applied level of stresses and strains [5]. The difficulty in combining all these factors into an universal criterion influenced the investigation of wrinkling to be carried out case by case, for specific sheet metal forming processes.

The first relevant work in the characterization of the wrinkling limit was performed by Yoshida et al. [6], in which proposed the creation of an experimental test in order to determine the tendency to wrinkle in sheet metal forming processes. The proposed test is designated by Yoshida buckling tests. Tomita and Shindo [7] analysed the previous tests with finite element method (ABAQUS). Cao et al. [8] proposed changes in the Yoshida buckling test, and considered a support on the blank in order to simulate experimentally the curvature of the sheet in the deep drawing operation, as well as the sheet contact with the tool.

The following studies attempt to predict the occurrence of wrinkling, independently of the Yoshida buckling tests. So, Kim and Yang [9] provided a comprehensive overview of the published literature in the field and proposed an energy based criterion to determine the onset of wrinkling in cylindrical, spherical and elliptical cup deep drawing.

Recently, Kasaei et al. [5] presented a new understanding on the deformation mechanics of flexible roll forming focused on the occurrence of flange wrinkling, where the determination of the wrinkling limits was made by means of a new theoretical and experimental methodology, based on the utilization of rectangular test specimens loaded in axial compression.

This paper aims to apply the wrinkling determination by Kasaei et al. [5] to AA1050-O and expand this methodology in order to analyse the thickness of the blank influence in the wrinkling limit.
2. Experimentation

2.1. Mechanical characterization of the material

This work was carried out on AA1050-O aluminium sheets with 1, 2, 3 and 4 mm of thickness. The mechanical characterization of the material was performed by means of tensile tests in an universal testing machine INSTRON, model 4507, with specimens that were cut out from the supplied sheets at 0° and 90° with respect to the rolling direction. The specimen geometry and parameters used in tensile tests followed the E8/E8M-09 standard [10].

The experimental values obtained for the modulus of elasticity $E$, the yield strength $\sigma_y$, the ultimate tensile strength $\sigma_{UTS}$, the elongation at break $A$ and the anisotropy coefficient $r$, at 0° and 90° with respect to the rolling direction, are provided in table 1. The resulting average stress–strain curve was approximated by the following Ludwik–Hollomon’s equation.

$$\sigma = 151.2e^{0.30} \text{ MPa} \quad (3)$$

Table 1 – Summary of the mechanical properties of the AA1050-O aluminium sheets.

<table>
<thead>
<tr>
<th>Modulus of elasticity $E$ (MPa)</th>
<th>Yield strength $\sigma_y$ (MPa)</th>
<th>Ultimate tensile strength $\sigma_{UTS}$ (MPa)</th>
<th>Anisotropy coefficient $r$</th>
<th>Elongation at break $A$ (%)</th>
</tr>
</thead>
<tbody>
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<td>72471.9</td>
<td>22.1</td>
<td>76.2</td>
<td>0.97</td>
<td>1.05</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>90°</td>
<td>47.0</td>
</tr>
</tbody>
</table>

2.2. Instability test

The instability tests, proposed for determining the formability limits by wrinkling, made use of the rectangular test specimen, figure 2 (a), loaded in axial compression. The specimens were cut from the supplied sheets, with different slenderness ratios ($l_0/w_0$), where $l_0$ is the initial length and $w_0$ is the initial width. This is because the slenderness ratio ($l_0/w_0$) influences collapse of the rectangular test specimens, by buckling due to plastic instability. The geometries used in tests can be visualized in tests plan, figure 2 (b). Sheets aligned at 0° and 90° to the rolling direction are used, in order to understand the influence of anisotropy in wrinkling limit.

In order to evaluate the thickness influence in the wrinkling limit, the instability tests are performed with AA1050-O aluminium sheets with 1, 2, 3 and 4 mm of thickness, as indicated in tests plan, figure 2 (b). Two tests are carried for each case, because it is necessary to perform a test with stops for measuring the extensions and another to acquire the evolution of the force with displacement along the test.

The instability tests were performed on the rectangular test specimen tool, figure 2 (c). This tool consists of two sheet holder (2), two horizontal guiding columns (3), two shims (4) and two die shoes (5). The sheet holder (2) provides the fixed end constraints of the specimen (1) in order to prevent deformation by pure bending. The shims (4) promote a distributed load on the specimen. The die shoe (5) serves to attach the testing equipment to the horizontal actuators of a double-action tool system, figure 2 (d) and (e). The horizontal guiding columns (3), ensure that the left and right fixed ends, of the rectangular test specimens, remain co-planar during axial compression. A simple screw blocking mechanism allows the testing equipment to be dismounted from the double-action tool system, without experiencing elastic recovery of the test samples. This is very important to measure the strains and the amplitude of the plastic instability wave caused by buckling and can also be utilized to evaluate the new values of strains and wave after elastic unloading.
The instability tests were performed in a hydraulic testing machine INSTRON, model 1200KN Satec. The horizontal actuators of a double-action tool system, figure 2 (d) and (e) were used, because they allow conversion of the vertical movement of the punch in a horizontal double acting motion, and this motion is transmitted to the rectangular test specimens tool. Double acting motion is required, to ensure that the wrinkling starts in the center of the specimen.

The experimental values of strains at several instants of the axial compression loading of the rectangular test specimens were determined by circle grid analysis. A grid of interlaced circles of 2 mm initial diameter was electrochemically etched on the surface of the specimens.

2.3. Swift cylindrical stamping tests

The Swift tests were performed for the validation of the wrinkling limit obtained through the instability tests. As the wrinkling limit was dependent of the thickness, it was necessary to perform the Swift tests with sheets of 1, 2, 3 and 4 mm of thickness. For each thickness, four tests were held to determine the strains, figure 3 (a), and this way an evolution of strains along the test was obtained. The diameter of the specimens was defined to 91 mm for a punch diameter of 50 mm to allow a stamping coefficient of approximately 0.55, this way a considerable flange was obtained in order to check the wrinkling.
### Table

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Diameter (mm)</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>91</td>
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</tr>
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<td>91</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>91</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total number of tests</strong></td>
<td><strong>16</strong></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>

(a)

Figure 3 – (a) Plan of experiments for the Swift tests; (b) Stamping tool; (c) Set punch-die for Swift tests.

The Swift cylindrical stamping tests were performed in a hydraulic testing machine INSTRON, model 1200KN Statec, with the stamping tool represented in figure 3 (b). The dimensions of the punch and the die are presented in figure 3 (c) and the clearance was defined for 0.91 to 1.30 mm of thickness [11]. Despite the use of sheets with 2, 3 and 4 mm of thickness, the stamping tool was kept safe, because the wrinkling arises at the beginning of the tests, with almost no penetration of the blank into the die. The blank holder was not utilized.

### 3. Finite element modelling

The numerical simulations of both instability and Swift tests, were performed using the commercial finite element computer program LS-Dyna. LS-Dyna is based on an explicit-dynamic elasto-plastic formulation and to be capable of taking into account the practical non-linearities in the geometry. Explicit formulation requires a time-step, as defined by equation 4.

\[
\Delta t \leq \frac{L_e}{\sqrt{E/\rho}}
\]

Wherein \(\Delta t\) is the time-step, \(L_e\) is the size of elements, \(E\) is modulus of elasticity of the material (table 1) and \(\rho\) is the material's density, 2705 kg/m³.

At the numerical simulation of the instability tests, the discretization of the specimens was made with square shell elements, using five integration points along the thickness. Material 39 of the LS-Dyna database was used, as it considers both anisotropy and the Hill plasticity criterion. The boundary conditions used at the edges of the specimen were: fixed in the thickness direction, and free movement in the length direction for compression of the specimen (see figure 4).
Figure 4 – Schematic representation of the boundary conditions set out in rectangular specimens of the instability tests.

The size of the elements, time-step and the specimen’s ends velocity were defined through sensitivity analyses, being chosen: 1 mm, 1E-5s and 0.1 mm/s, respectively.

In the numerical simulation of the Swift tests, the used parameters were equal to those used in the numerical simulation of the instability tests, except for the velocity of the test (velocity of the punch), that was set to 1 mm/s. The die and the punch were modelled as analytical shell rigid bodies, because their deformation is negligible during the tests. The Coulomb friction law was employed with an assumed friction coefficient of $\mu=0.1$ between the blank and the punch, and the blank and the die.

4. Results and discussion

4.1. Instability test

The experimental results for 1 mm thickness specimens showed that the screws tightening in the fixing of the specimen applied a bend in the specimen, leading to the instability before the experimental test started. This problem occurs due to the material's weak mechanical properties and it's mild state. For the 2, 3 and 4 mm of thickness cases, this problem did not occur.

Kim and Yang (2003) proposed an energy-based criterion, built upon the observation that the maximum axial compression load of rectangular sheet test specimens, corresponds to a bifurcation point, after which, the deformation energy along the local buckled configuration should always be smaller than the alternative primary evolution path corresponding to ideal homogeneous compression. The bifurcation point (point of maximum force) in the compression load was observed for all the tests (see figure 5).

Figure 5 – (a) Evolution of the force with the displacement obtained in the experimental instability tests carried out with 2mm thickness specimen and lengths of 20, 35, 50 and 100 mm; (b) Evolution of the force with the displacement obtained in the experimental instability tests carried out with specimen with 50 mm length specimen, and thicknesses of 2, 3 and 4mm.

Figure 5 (a) shows that when the slenderness ratio increases the instability is achieved for smaller displacements, i.e., for lower values of material deformation and thus, lower force values. This is,
because up to the point of instability, the material is in a state of uniaxial compression, thus increasing the force with displacement.

With increasing thickness, instability appears for larger displacement values, namely, larger material deformations and larger force values, figure 5 (b).

The numerical validation of the experimental work was performed by analyzing the evolution of force with displacement, and of the strains along the tests. The evolution of force with displacement obtained experimentally (EXP) and numerically (FEM) can be visualized in figure 6 (b) for a specimen with 1 mm and 50 mm of thickness and length, respectively.

![Figura 6](image)

Figura 6 – (a) Schematic representation of early wrinkling not uniform across the width of the sheet specimen. (Kasaei et al., [5]); Evolution of the force with displacement obtained experimental and numerically in the instability tests (b) performed on 1 mm thickness and 50 mm length specimen (c) performed on 4mm thickness, 20mm length and 50.91 mm width specimen.

The differences between the experimental and numerical results are attributed to the experimental observation that the onset of wrinkling is not attained simultaneously along the entire width of the rectangular sheet test specimens (see figure 6 (a)) and this problem occurs due to a lack of co-planarity in the tests [5]. This is more relevant for the specimens with largest slenderness ratio \((l_0/w_0)\) of the test specimen and for lower thicknesses, because instability is achieved for smaller displacements. To achieve the instability it is necessary to have a certain critical axial compressive stress \(\sigma_{crit}\), given by equation 5 [5].

\[
\sigma_{crit} = \frac{F_{fem}}{w_0 t_0} = \frac{F_{exp}}{w_0 t_0} \quad (5)
\]

Where \(F_{fem}\) and \(F_{exp}\) are the experimental and numerical forces, \(w_0\) is the initial width of the rectangular sheet test specimen, \(w_0'\) is the initial effective width and \(t_0\) is the initial sheet thickness. This equation allows the calculation of the initial effective width. The results obtained through numerical simulations, using the effective width, show a better correlation between the experimental and numerical results (see figure 6 (b)). This problem is negligible for specimens with 4 mm thickness and 20 mm length, figure 6 (c), because the specimen is thick and witnesses a smaller slenderness ratio \((l_0/w_0)\).

The evolution of strains with normalized amplitude \(h/L\), where \(h\) is the amplitude of the plastic instability wave at a certain instant of time and \(L\) is the corresponding unsupported distance between the left and
right fixed ends of the specimens, figure 7 (a), obtained experimentally (EXP) and numerically (FEM) can be visualized in figure 7 (c).

![Graph showing strain and force along instability tests](image)

Figure 7 – (a) Schematic representation of the beginning and end of the test instability; (b) Schematic representation of the directions of the principal in-plane strains of the sheet; (c) Evolution of the strains and the force along the instability tests on 2mm thickness and 50 mm length specimen.

This result was obtained using a specimen with 2 mm thickness and 50 mm length, but the evolution of strains is very similar for the other cases. Where the lines intercept the y-axis, the critical in-plane strains ($\varepsilon_1^{\text{crit}}$, $\varepsilon_2^{\text{crit}}$) can be read, being this the precise moment instability is attained and the wrinkling phenomenon starts. In this instant of time, the longitudinal strain is $\varepsilon_2^{\text{crit}}$ and transversal strain is $\varepsilon_1^{\text{crit}}$ (see figure 7(b)).

4.2. Characterization of the wrinkling limit

With the values of critical in-plane strain obtained for different tests, with different slenderness ratio ($l_0/w_0$), it is possible to plot the formability limits by wrinkling in the principal strain space and in the triaxiality plane, figure 8 (a) and (b), respectively.

With the decreasing of the slenderness ratio, the material behaviour changes from homogeneous compression, to compression under plane strain conditions that are typical of sheet-bulk metal forming processes [12]. This is noticeable in figure 8 (a) and (b), attaining a more compressive regime, as the slenderness ratio decreases.

Figure 8 (c) and (d) presents the wrinkling limit curve for AA1050-O aluminium sheets with 1, 2, 3 and 4 mm of thickness. It should be noted that the sheet thickness has a significant influence on the wrinkling limit. This fact is noticeable in the tests, because with the increasing of thickness, instability is reached for larger displacements, and thus, larger material deformation.

4.3. Validation of wrinkling limit

The Swift cylindrical stamping tests were performed for the validation of the wrinkling limit, obtained through the instability tests. Figure 9 presents the deformation history of the flange area for the specimen with 2 mm of thickness.
Figure 8 – (a) Representation of the wrinkling limit for the AA1050-O aluminium sheet with 1 mm of thickness in the principal strain plane; (b) Representation of the wrinkling limit for the AA1050-O aluminium sheet with 1 mm of thickness in the triaxiality plane; (c) Wrinkling limits represented in the principal strain plane for the AA1050-O aluminium with 1, 2, 3 and 4 mm of thickness; (d) Wrinkling limits represented in the triaxiality plane for the AA1050-O aluminium with 1, 2, 3 and 4 mm of thickness.

Deformation history in the top and the valley of the wrinkles are similar until instability takes place, after which, deformation increases for tensile strains, with the valley remaining in a compressive strain store. Instability arises when the wrinkling limit and the deformation's trajectory intersect. The formability limits, characterized by the wrinkling of AA1050-O aluminium sheet with thicknesses of 1, 2, 3 and 4 mm, have been successfully validated by the Swift tests.
5. Conclusion

This document proposed the characterization of the wrinkling limit through instability tests, by means of experimental and numerical work. The test specimen is compressed till instability is achieved, with the consequent wrinkling in the specimen. The principal strains pair achieved at the instability instant, is called the critical strains pair, which was used to trace the wrinkling limit.

The sheet thickness has a significant influence on the wrinkling limit. This fact is noticeable in the instability tests, as an increase of thickness, instability occurs at larger displacements, i.e, at larger material deformations. The characterized wrinkling limits were then successfully validated by Swift tests.

References