Experimental research of formability limits in different thicknesses of polycarbonate sheets

A Rosa-Sainz¹, JP Magrinho², M B Silva³*, G Centeno¹, A J Martínez-Donaire¹, C Vallellano¹

¹Department of Mechanical and Manufacturing Engineering, University of Seville, Camino de los Descubrimientos s/n 41092, Seville (Spain)
²CENTIMFE, Technological Center for Mouldmaking, Special Tooling and Plastic Industries, Zona Industrial, Rua da Espanha, Lote 8, 2430-028 Marinha Grande (Portugal)
³IDMEC, Instituto Superior Tecnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001, Lisbon (Portugal)

beatriz.silva@tecnico.ulisboa.pt

Abstract. This experimental investigation evaluates the methodologies for determining the forming limits by necking and fracture in polycarbonate (PC) sheets. The proposed approaches are based on two methodologies that are commonly utilized in sheet metal forming. To that end, Nakajima tests for polymer specimens with different strain loading paths were carried out for 1 mm, 2 mm and 3 mm thickness. The evaluation of the principal strains was accomplished by means of Digital Image Correlation (DIC) and thickness measurements to obtain failure strains were performed. The experimental results highlighted the different behaviour attained in polymers and metals, and the need of establishing a suitable adaptation of the methodologies used in sheet metal forming, especially due to the elastic recovery of polymers that cannot be neglected. This analysis allowed obtaining accurate formability limits by necking and by fracture for the PC sheets of 1, 2 and 3 mm of thickness, additionally these results were compared with the formability limits for PVC sheet of 3 mm of thickness. The representation of these formability limits within the principal strain space allowed establishing a general framework for analysing the fracture limit, which is the relevant forming limit in incremental sheet forming processes.

1. Introduction

Polycarbonate is a kind of thermoplastic polymer widely used in the manufacturing industry that presents several advantages such as transparency, high ductility, impact resistance and lightweight. The shaping of this kind of polymers is commonly performed through operations involving heating, forming and cooling operations, being these only economically viable for mass production.

Currently, industry is directed to low volume, lightweight, high quality and customization of products. These characteristics lead to the development of flexible processes, short forming cycles, short development and production times, which are compatible with rapid prototyping and small-batch production, as is the case of the incremental forming of polymeric sheets [1].

In the mid ’60s of last century, several conventional sheet and bulk metal forming operations were applied to cold plastic deformation for polymers, as discussed in Shaw [2], who identified the most relevant ones. Cold forming of polymers requires less energy and present shorter time cycles, better
mechanical properties as well as simpler and less expensive tooling. Parallel, Caddell et al. [3] were pioneers in the characterization of the polymer's behaviour in cold forming.

During the last decade, advances in computer assisted manufacturing processes have motivated the interest in developing procedures with a higher level of flexibility than other conventional plastic deformation based processes. For example, Single Point Incremental Forming (SPIF) raised the interest in cold forming of polymers [1], including its formability and failure [4,5].

The work by Marques et al. [6] studied four different thermoplastic sheets: polyamide (PA), polycarbonate (PC), polyethylene terephthalate (PET) and polyvinylchloride (PVC). Formability limits were determined through circle grid analysis (CGA) for the determination of the necking limit usually expressed as the forming limit curve (FLC), and the fracture thickness measurements to obtain the ‘gauge length’ strains for defining the so-called fracture forming limit line (FFL). The results showed that FLC and FFL should be considered as a unique limit. Nevertheless, due to the stable neck propagation in polymers after the onset of necking CGA is not the best methodology to determine the necking limit [7].

With the aim of finding a better methodology to determine formability limits in polymer sheets, this work revisits the methodology for assessing the formability limits by necking and by fracture of polymers, proposing an adaptation of the sheet metal forming procedures. The experimental work is performed by means of Nakajima tests with 4 different geometries to obtain strain paths from tensile strain towards equi-biaxial strain for 1, 2 and 3 mm of thickness polycarbonate sheets. Additionally, the experimental work was extended to 3 mm of thickness Polyvinyl chloride (PVC) sheets.

2. Experimentation

Nakajima tests were performed to obtain the formability limits by necking and fracture of 1, 2 and 3 mm thickness PC sheet and 3mm PVC sheet. The tests were carried out following the standard ISO 12004-2 [8] using a universal sheet testing machine Erichsen model 142-20 at room temperature (25 °C). The measurements of the principal strains within the deforming area at the vicinity of the zones where cracks appeared were carried out using a digital image correlation (DIC) ARAMIS® v6.2.0-6 system (see the schematic representation in Figure 1a). Four geometries were considered to achieve different strain loading paths: Tensile Strain (TS), Plane Strain (PS), Biaxial Strain (BS) and Equi-biaxial Strain (EBS) (see the schematic specimens shapes in Figure 1b). Three repetitions were made for each Nakajima test specimen geometry and two layers of Polytetrafluoroethylene were sandwiched with three layers of Vaseline between the punch and the polymeric sheet specimen to minimize the friction. The geometry of the specimens and the operating conditions are described in a previous paper [9].

2.1 Necking overview

Necking is a failure mode that occurs by tension, where relatively large amounts of strain are disproportionately located in a small region of the material. Formability limits by necking within the
principal strain space are determined by adapting two methodologies commonly applied for metals [10] to polymeric sheet: (i) time-dependent and (ii) flat-valley.

2.1.1 Time-dependent methodology
The time-dependent methodology is based on the experimental indication of the neck initiation and its progress [10]. Figure 2 presents a schematic evolution of the major strain temporal analysis and its first-time derivative, or major strain rate, for a series of points along a section perpendicular to the crack. In a previous work [9], the necking propagation in polymers was studied showing that the neck starts on a different cross-section of the specimen than fracture. In this sense, an adaptation of the original methodology was required [10]. The procedure was performed using the steps described below:

a) Identification of the two reference points at the necking zone: point A and point B. Point A corresponds to the point where necking starts and point B is the first point where the strain starts ceasing. The identification of these points is carried out with the representation of the major strain with time for several points along a section perpendicular to the site of necking (e.g. points A, P₁, …, Pₙ, B) (see Figure 2a).

b) Identification of the boundary of the instability region (i.e. between point A and point B). This allows observing how the points within this region have a monotonical increase of strains, ceasing at point B (see Figure 2a).

c) Representation of the strain rate evolution of point B with time (see Figure 2b). The methodology assumes that at the instant in which the strain rate for point B reaches a local maximum (Point B strain rate max in Figure 2b) the onset of necking takes place.

d) The limit strains at the onset of necking will correspond to the principal strains at Point A (depicted in Figure 2a) at the time instant “t necking” (See Figure 2b).

![Figure 2](image_url)

**Figure 2.** Schematic representation of the time-dependent methodology. (a) Evolution of major strains with time for the necking region, and (b) time-dependent approach, adapted from [10].

2.1.2 Flat-valley methodology
The flat-valley approach is based on the direct observation and analysis of displacements in the superficial layer of the sheet specimen obtained by DIC measurements to identify the instant of time corresponding to the onset of necking [10]. The procedure was performed using the following steps:

a) Figure 3a shows the schematic evolution of the Z-displacement (normal direction to the surface) over the X-position along a section perpendicular to the necking of a Nakajima test, and each evolution corresponds to an instant of time.

b) The previous representation allows different profiles. The profile evolution before the onset of necking follows the punch geometry (stage t₁ in Figure 3a), the onset of necking stage reveals a flat profile or flat valley (stage t₂ in Figure 3a) and after the onset of necking the valley is visible (stage t₃ in Figure 3a).
c) A complementary way to detect the onset of necking is performed considering the temporal evolution of the Z-displacement spatial derivative of the different stages of the same section perpendicular to the necking area (see Figure 3b). The onset of necking corresponds to the instant in which the slope remains locally constant (green curve in Figure 3b).

![Figure 3](image-url)  
**Figure 3.** Schematic representation of flat-valley approach: (a) Z-displacement over the X position and (b) temporal evolution of the Z-displacement spatial derivative, adapted from [10].

### 2.2 Fracture limits

The procedure for determining the formability limits by fracture is based on the measurement of the fracture thickness from the fractographies of the fractured specimens [11]. In this sense, minor strain at fracture ($\varepsilon_{2f}^*$) and major strain at fracture ($\varepsilon_{1f}^*$) were calculated considering that the local loading path slope of the principal $\beta^*$ remains constant, thus being $\beta^* = \frac{d\varepsilon_{2}^{\text{DIC}}}{d\varepsilon_{1}^{\text{DIC}}}$ (i.e. with the last caption of the DIC system). Due to the relatively low value of the Young modulus of elasticity (2.4 GPa) compared to metallic materials, a notable material elastic recovery is produced after fracture. Hence, the last caption of the principal strains via the DIC system was considered to define the forming fracture limit (FFL). In the schematic view in Figure 4 of a tensile strain subjected to a Nakajima test, necking takes place when the specimen is subjected to a certain stress level. The necking propagation initiates showing the difference between the necking zone and the elongated area. Finally, the fracture occurs in the specimen test. The complete methodology is detailed in the previous paper Rosa-Sainz et al. [9].

![Figure 4](image-url)  
**Figure 4.** Tensile strain Nakajima specimen: (a) schematic representation along deformation from local instability by necking until fracture and (b) fractography of a TS PC specimen with 1 mm thickness, adapted from [9].

### 3. Results and discussion

#### 3.1 Necking results

This section is separated into (i) necking results obtained in TS and PS specimens, (ii) necking results obtained in BS specimen and (iii) absence of necking in EBS specimen. The overall content shown in this paper are the main results of the investigation, detailed results can be accessed in [9,12].

**3.1.1 Onset of necking in Tensile Strain and Plane Strain**

Figure 5 and 6 present the application of the two approaches to the TS Nakajima specimen for 2 mm thickness. Focusing on 2 mm thickness (Figure 5a and 5b), through a time-dependent approach, points A and B, which define the instability region, were identified. Point B corresponds to the first point where
the strain starts ceasing (see Figure 5a). The strain rate of point B is presented in Figure 5b, where its local maximum can be identified \( \dot{\varepsilon}_{B,\text{max}} \) and thus the time instant at the onset of necking. This approach allowed to assess the onset of necking, which occurs at point A for the strains at the time instant \( t_{\text{necking}} \) (see Figure 5b). In the case of the 1 [9] and 3 mm thickness PC sheet, the application of the methodology was the same as for 2 mm thickness PC sheet, and similar results were also obtained for 3 mm thickness PVC sheet.

**Figure 5.** Time-dependent in TS Nakajima specimen: (a) Experimental evolution of major strain with time along the target section and (b) methodology in the case of 2 mm thickness PC sheet.

The flat-valley approach is presented in Figure 6. Focusing on 2 mm thickness PC sheet, the Z-displacement along a section perpendicular to the necking region presented in Figure 6a allowed identifying the instant at which the onset of necking initiates (highlighted in green). In this sense, the thickness of the central region reduces sensibly faster than the adjacent regions and a flatten profile is visible, corresponding to the onset of necking. In Figure 6b the spatial derivative of the Z-displacement along the selected section is presented for the case of 2 mm thickness PC sheet. Highlighted in green is the onset of necking that corresponds to the instant at which the slope remains locally constant. In Figure 6b is also presented the stage before (highlighted in blue) and after (Figure 6b highlighted in red) the onset of necking stage. In the case of 1 [9] and 3 mm thickness, the application of the methodology was the same as for the case of 2 mm thickness PC sheet. Similar results were obtained with the application of the presented methodology for 3 mm thickness PVC sheet. The application of the methodologies for Nakajima PS specimen was similar to the TS specimen, the results are exposed in a previous paper by Rosa-Sainz et al. [12].

### 3.1.2 Onset of necking in Biaxial Strain

Figure 7 represents the application of the two approaches to the BS Nakajima specimen for 1 mm sheet thickness. The time-dependent approach allowed determining the limit strains at the onset of necking that corresponds to point A strains \( t_{\text{necking}} \) for both thicknesses (Figure 7a). Figure 7 (1 mm thickness BS specimen) show that the flat-valley is not as direct as time-dependent, providing an interval of stages in which the onset of necking occurs for both thicknesses (Figure 7b). On the other hand, the Z displacement does not show a changed slope and the flat valley profile is not visible. The derivative of Z-displacement does not show a difference in the evolution of the curves (See Figure 6b). In this sense, it could be necessary to increase the resolution of the DIC system to observe changes at the outer surface topology [9]. Similar results were obtained with the application of the presented methodology for 2 mm thickness PC.
Figure 6. Flat-valley in TS Nakajima specimen: (a) Z-displacement along the selected section and (b) the spatial derivative in the case of 2 mm thickness PC sheet.

Figure 7. Application of the onset of necking strains methodologies for a BS Nakajima specimen of 1 mm thickness PC sheet: (a) time-dependent and (b) flat-valley, adapted from [9].

Figure 8. (a) Force displacement evolution for the Nakajima tests of PVC sheets with 3 mm of thickness. Major strain distribution obtained for (b) Nakajima BS and (c) EBS tests.
3.1.3 Absence of necking
The absence of necking occurred for the EBS Nakajima specimen of 1, and 2 mm thickness PC sheet and for the BS and EBS Nakajima specimen for 3 mm thickness PC and PVC sheet. The time-dependent approach revealed that the major strain at a series of points along a section perpendicular to the crack showed no ceasing, and the flat-valley approach applied to the specimens also reaffirmed that necking was not a failure mode for the above-mentioned Nakajima specimens. Both methodologies allowed showing the absence of necking under equi-biaxial conditions for PC sheet in all the thicknesses. An extended explanation of these results can be found in Rosa-Sainz et al. [9].

The results for the BS and EBS Nakajima specimens of 3 mm thickness PC and PVC sheet failure occurred by fracture without the occurrence of necking. Figure 8a presents the evolution of force with displacement for all the Nakajima geometries for 3 mm PVC sheet, in which for the TS and PS a slight decrease at the instant of necking is visible, while for the BS and EBS the evolution is continuous with no evidence of necking occurrence. This fact is evidenced by the uniform distribution of the major strain for Nakajima BS (see Figure 8b) and EBS tests (Figure 8c).

3.2 Formability limits in principal strain space
The formability limits by necking and by fracture were determined by means of Nakajima tests using the methodologies previously described in section 2. Figure 9 represents the formability limits (FLC points and FFL) for the 1, 2 and 3 mm thickness PC sheet and 3 mm thickness PVC sheet within principal strain space.

![Figure 9](image-url) Figure 9. Formability limits for 1, 2 and 3 mm thickness PC sheet and 3 mm thickness PVC sheet evaluated by means of Nakajima tests using TS, PS, BS and EBS specimens. The open circular markers correspond to the necking points and the square markers to the fracture points.

In Figure 9 the necking points or FLC points (circular markers) for 1, 2 and 3 mm thickness PC sheet and 3 mm thickness PVC sheet are presented, the authors opted to represent only the points due to the fact that not all Nakajima geometries allowed to determine the necking points. The necking points, show a different behaviour from those previously determined by Marques et al. [6]. The differences could be related to the use of a DIC system that provides a more accurate definition of the onset of necking due to the steady propagation of the neck. This is because the FLC for polymers would not follow a regular shape such as the typical V-shape of metals and we do not have values for the biaxial deformation.

On the other hand, the FFL’s for all the materials and thicknesses were built by using the major and minor principal strains evaluated at the last DIC measurements before fracture. Figure 9 reveal that an increase of the sheet thickness leads to a slight enhancement of formability increasing the strain values of the formability limits by fracture. This behavior is not so evident in the necking points and a future study with intermediate Nakajima geometry specimens will be made.
The assessment of these formability limits for the case of 1 mm thickness PC sheet is further explained in Rosa-Sainz et al. [9].

4. Conclusions

The methodologies presented have allowed the successful determination of necking and fracture limits for PC sheet of 1, 2 and 3 mm thickness and PVC sheet of 3 mm thickness. The authors enlarged the application of previous work [9 and 12], determination by means of two approaches usually used for metal sheets, to a thicker sheet and a new polymer. The utilization of a DIC system was appropriate to assess the experimental measurements of the strains despite the typical necking propagation of polymers, where other techniques such as CGA were revealed inappropriate. The 3 mm thickness PC and PVC sheets revealed that no necking was obtained for the BS and EBS Nakajima tests, due to this conclusions additional Nakajima geometries should be used to better characterize the necking limit. The increase of thickness for 1, 2 and 3 mm PC sheets increased the principal strain values defining the formability limits by fracture.

Acknowledgements

The authors acknowledge the funding provided by Grants US-1263138 and P18-RT-3866 within the framework US/JUNTA/FEDER,UE, the Grant PGC2018-095508-B-I00 financed by MCI/AEI/FEDER,UE and the Fundação para a Ciência e da Tecnologia of Portugal through the project LAETA-UIDB/50022/2020.

References

[1] Franzen V, Kwiatkowski L, Martins P A F, Tekkaya A E 2009 Single Point Incremental Forming of PVC J. Mater. Process. Technol. 209 (1) pp 462–469
[2] Shaw M T 1980 Cold Forming of Polymeric Materials Annu. Rev Mater. Sci. 10 (1) pp 19–42
[3] Caddell R M, Raghava R S, Atkins A G 1974 Pressure Dependent Yield Criteria for Polymers. Mater. Sci. Eng. 13 (2) pp 113–120
[4] Silva M B, Alves L M, Martins P A F 2010 Single Point Incremental Forming of PVC: Experimental Findings and Theoretical Interpretation Eur. J. Mech. A/ Solids 29 (4) pp 557–566
[5] Bagudanch I, García-Romeu M L, Sabater M 2016 Incremental Forming of Polymers: Process Parameters Selection from the Perspective of Electric Energy Consumption and Cost J. Clean. Prod. 112 pp 1013–1024
[6] Marques T A, Silva M B, Martins P A F 2012 On the Potential of Single Point Incremental Forming of Sheet Polymer Parts Int. J. Adv. Manuf. Technol. 60 (1–4) pp 75–86
[7] Carothers W H, Hill J W 1932 Studies of Polymerization and Ring Formation XV Artificial Fibers from Synthetic Linear Condensation Superpolymers J. Am. Chem. Soc. 54 (4) pp 1579–1587
[8] ISO12004-2 Metallic Materials-Sheet and Strip-Determination of Forming Limit Curves Part 2: Determination of Forming Limit Curves in Laboratory 2008 Geneva Switzerland
[9] Rosa-Sainz A, Centeno G, Silva M B, López-Fernández A J, Martínez-Donaire A J, Valrellano C 2020 On the Determination of Forming Limits in Polycarbonate Sheets Materials 13 (4) pp 1–17
[10] Martínez-Donaire A J, García-Lomas F J, Valrellano C 2014 New Approaches to Detect the Onset of Localised Necking in Sheets under Through-Thickness Strain Gradients Mater. Des. 57 pp 135–145
[11] Centeno G, Martínez-Donaire A J, Morales-Palma D, Valrellano C, Silva M B, Martins P A F 2015 Novel Experimental Techniques for the Determination of the Forming Limits at Necking and Fracture Materials Forming and Machining, Research and Development ed Davim J P (Cambridge, UK : Woodhead Publishing) pp 1–24
[12] Rosa-Sainz A, Centeno G, Silva M B, Valrellano C 2021 Experimental Failure Analysis in Polycarbonate Sheet Deformed by Spif J. Manuf. Process. 64 pp 1153-1168