Materials Research Proceedings 41 (2024) 1569-1578 https://doi.org/10.21741/9781644903131-174

Necking detection in stretch-bent materials exhibiting the Portevin-Le Chatelier effect

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Keywords: Necking, Nakazima, PLC Effect, Stretch-Bending, Time-Dependent, Flat Valley Method

Abstract. In recent years, there has been increasing societal awareness of the carbon dioxide (CO_2) footprint resulting from individual actions and lifestyles. One of the research actions is focused on the development of eco-friendly alloys with more recycled scrap material in order to reduce emissions, but this can also result in greater variability of material properties. In this context, accurately characterizing the formability limits of materials is of paramount importance for optimizing manufacturing processes. Although ISO 12004-2:2008 standard is commonly used for necking detection, recent years have seen time-dependent methods yield more accurate predictions. Nevertheless, in materials exhibiting the Portevin-Le Chatelier (PLC) effect, such as some common lightweight alloys used in automotive and aeronautics, necking detection introduces significant challenges, and even more so when the material is subjected to severe local stretch-bending states. In this work, various necking detection techniques were employed to analyze their capabilities in a series of stretch-bending experiments over a 2.94 mm thick AA5754H11 PLC-driven material.

Introduction

Given the alarming predictions of reaching the CO_2 capacity threshold in the next 25 years, there is a concerted effort to implement new trends and technologies to reduce emissions. Among others, the most popular are: 1) shift towards more flexible manufacturing processes, including incremental sheet forming methods [1], 2) maximizing the material use, especially in high-CO_2 emission industries such as steel and aluminum production, and 3) developing eco-friendly alloys with more recycled scrap material can reduce emissions [2], although this may result in greater variability of material properties. In this context, the accurate knowledge of the limit strains at necking and at fracture is crucial to optimize the planning of the manufacturing stages.

The use of lightweight materials exhibiting the Portevin-Le Chatelier (PLC) effect, such as 2024-O or 5754-O aluminum alloys, is very common in the industrial manufacturing of sheet metal parts in both the aerospace and automotive industries.

It is well established that the PLC effect is attributed to dynamic interactions between mobile solute atoms and dislocations, termed dynamic strain ageing (DSA) [3]. Plastic flow instabilities associated with dynamic strain ageing (DSA) can be exhibited during plastic straining of Al-Mg alloys [4-6], such as AA5754. These are manifested by the appearance and propagation of localized deformation bands (PLC bands) along the specimen, which not only generates undesirable traces

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on the product surface due to the discontinuous deformation process but can also reduce the ductility of the alloy [3].

The most common failure mechanism in conventional sheet metal forming, such as stamping or stretching, is the appearance of tensile plastic instability and the subsequent tearing and fracture of the specimen. Many works have focused on accurately determining the onset of necking by proposing different experimental procedures and techniques [7-11]. The standardized position-dependent ISO 12004-2:2008 [7] is commonly used to establish the Forming Limit Curve (FLC) at necking using the Marciniak and Nakazima-type tests, i.e., situations in which the strain/stress gradient does not play an important role. However, in recent years, both time-dependent (t-d) and time-position dependent methods have been pointed out to yield more accurate predictions [8-11], as well as some of these approaches are able to broaden their applicability to more general cases under simultaneous action of stretching and bending [8,12].

These experimental methodologies are mainly based on the temporal analysis of the time derivatives of the major and/or thickness strains over the deformation process. Therefore, their application to materials that exhibit an unsteady strain evolution due to the formation of PLC bands that clearly impact the strain rate computation is complex and has not been thoroughly investigated. Furthermore, when the material is subjected to mild or severe stretch-bending conditions, because the standard ISO 12004-2:2008 cannot be applied, it seems to be a challenge.

The objective of this work consists of applying various existing necking detection techniques to analyze their predictive capabilities in the light of stretch-bending experiments with cylindrical punches of different radii over an AA5754H11 PLC driven material with 2.94 mm thickness. In particular, the radius R20 and R7.5 mm are selected for the analysis presented herein. It is pointed out that time-dependent methods, based on the analysis of time derivatives of the local strains, must be applied carefully to obtain reliable estimations, whereas local curvature evaluation methods, such as the flat-valley method, which focuses on analyzing displacements at the outer sheet surface, accurately assess the onset of necking.

Necking Detection Techniques

In this section, a summary of the fundamentals of the three experimental approaches analyzed in this contribution is presented. Along with the standardized ISO 12004-2:2008 method [7], the t-d method and a time-position dependent approach known as flat-valley, both previously proposed by the authors [8], have been analyzed. It should be noted that t-d and flat-valley are local approaches, not restricted to the FLC assessment, and therefore also applicable to stretch-bending tests.

ISO 12004-2:2008 methodology

The ISO12004-2:2008 procedure is a position-dependent method based on the analysis of the major strain profile along a cross section perpendicular to the fracture zone just before the occurrence of the fracture. Briefly, the procedure steps are the following: 1) Defining the crack position, 2) marking the necking region width or the inner limits of the fit windows, 3) obtaining the outer limits of the fit windows, 4) determining the limit major strain by fitting an inverse parabola using the experimental data within the fit windows, 5) determining the limit thickness strain by fitting another inverse parabola and 6) estimating the limit minor strain by applying volume conservation. Further details about the methodology can be found in [7].

Time-dependent method by Martinez-Donaire et al.

The t-d method [8] is based on the physical fundamentals of the necking process to detect the onset of the plastic instability. This method makes use of the temporal analysis of the major strain distribution and its first derivative over time at various points along a cross section perpendicular to the fracture zone. Fig. 1a shows a schematic of the time evolution of the mayor strain and its time derivative at two points, A and B, located in a section perpedicular to the necking region. The procedure can be divided in the following steps:

1) Obtaining the necking zone width. The last points on both sides of the crack that stop deforming and reach a null strain rate (marked as Point A in Fig. 1a) just before the fracture occurrence are identified. The zone between them defines the area where necking took place.

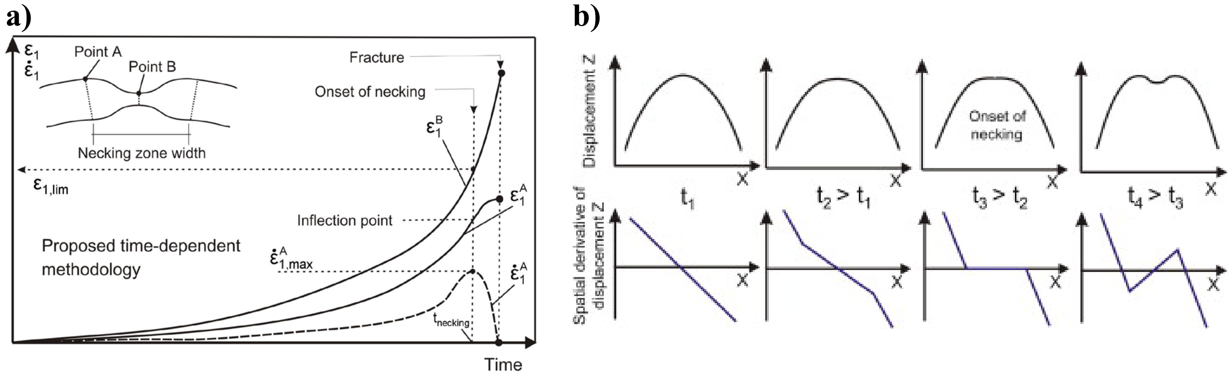

Fig. 1: Schematic of the t-d method (a) and the flat-valley method (b) to detect the onset of necking and estimate the limit strains [8].

2) Determining the onset of necking ($t_{necking}$). It was established that the plastic instability starts when the "strain rate" at the boundary of the necking zone (Point A) reaches a maximum. This event reveals that the deformation is just about to localize within the necking zone (region A-B-A in Fig. 1a), defining the time at which necking begins.
3) Identifying the fracture point. The point at which the fracture occurs (Point B) can be identified by detecting the highest strain curve during the whole deformation process (see the evolution of ε_1^B in Fig. 1a).
4) Determining the limit major and minor strain at necking $\varepsilon_{1,lim}$ and $\varepsilon_{2,lim}$.These are defined as the values of major and minor strain at point B at the time $t_{necking}$, respectively.

An analogous method but based on the analysis of the thickness strain (ε_3) can be also proposed with similar results [8].

Flat-valley method

The flat-valley method [8,12] focuses on the direct observation and analysis of the curvature of the topology of the outer surface of the specimen during the test. In particular, it analyzes the time evolution of the displacement perpendicular to the plane of the non-deformed specimen (Z axis) and its spatial derivative along a section perpendicular to the failure region. According to this, the flat-valley can be categorized as a time-position dependent method.

Fig. 1b (top) depicts a schematic of the Z-displacement in a section perpendicular to the fracture region at different times (t_1 denotes a time far from necking and t_4 denotes a time just before fracture). As can be seen, far from the instant failure, e.g., in t_1, the surface of the sheet deforms following the curvature imposed by the tool, in this case a hemispherical or cylindrical punch. Later, this curve begins to flatten in a certain region, see t_2, becoming flat at a certain time (t_3), until finally a necking valley is observed at time t_4.

When the profile becomes flat, the sheet begins to deform independently of the curvature imposed by the punch. This fact physically corresponds to the appearance of the neck, i.e. $t_{necking} = t_3$ in Fig. 1b. This flattening process can be clearly identified by calculating the first spatial derivative of the Z-displacement (Fig. 1b, bottom). Thus, it is hypothesized that necking begins when the slope in the first spatial derivative of the Z-displacement remains constant, not necessarily zero, within the necking region. Finally, as in the t-d method, once the onset of necking is identified, the major and minor limit strains can be obtained at their corresponding strain curve at the most strained point at a time equal to $t_{necking}$.

Experimental campaign

The material selected for this study was an AA5754H11 with a 2.94 mm thickness. This is an aluminum alloy widely used in automotive industry that exhibits the formation of PLC bands during the plastic deformation.

Several stretch-bending tests using cylindrical punches of two radii, R20 and R7.5 mm, were performed on a universal sheet metal testing machine Erichsen 142-40 (Fig.s 2a and 2b). These punch diameters were selected to achieve two clearly different bending strain gradients: a smooth/mild gradient for R20 mm and a severe gradient for R7.5 mm. These values are very common in stretch-bending operations in industrial practice as well as automotive stamping dies.

The testing parameters were selected according to standard ISO 12004-2:2008. The punch speed was set to 1 mm/s and the tribology system was a combination of PTFE sheets and vaseline between the punch and the metal sheet. A blank-holder force of 400KN and a draw-bead system was used to clamp the specimen.

Fig. 2c shows the geometry of 55 mm width samples tested to reproduce strain paths close to plane strain conditions.

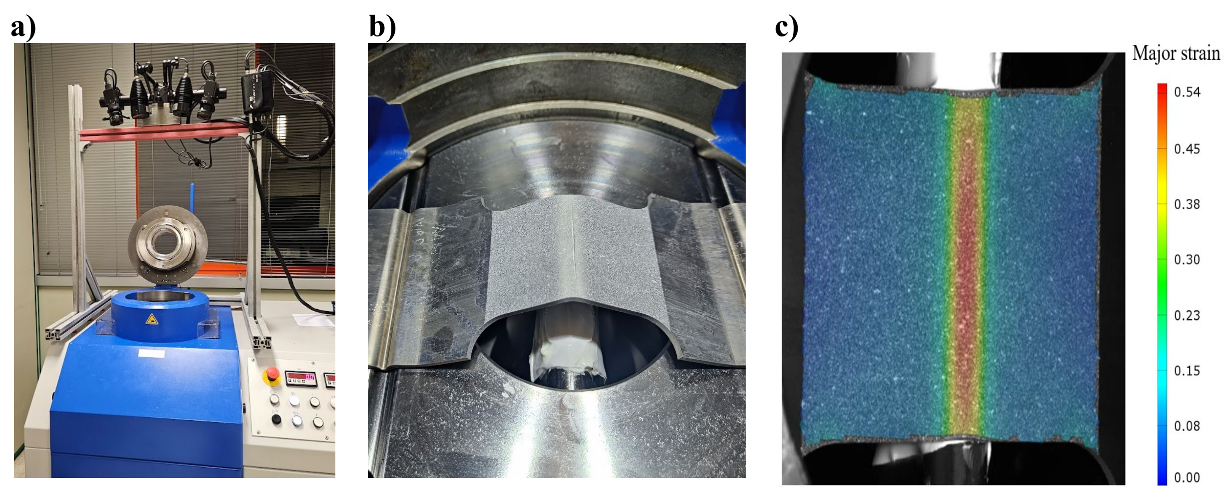

Fig. 2: a) Erichsen machine, DIC system and experimental setup*, b) sample with R20 mm radius punch and c) major strain data from DIC over the specimen geometry under near plane strain conditions*

Two 5-megapixel digital CCD cameras captured images during the whole deformation process at a rate of 15 frames per second. The strain contour on the outer surface was evaluated via Digital Image Correlation (DIC) technique using ARAMIS® (Fig. 2c). To define the optimum values for each gradient severity, i.e. for each punch radius, a study of sensitivity was performed by using several combinations of facet size and facet step in the DIC software.

Experimental results and comparative analysis for necking prediction

In this section, the experimental results obtained and the capabilities for predicting the limit strains at the onset of necking are analyzed using the standard ISO 12004-2, the t-d method, and the flat-valley method.

The application of each of these criteria requires measuring by DIC the temporal and spatial distribution of the principal strains on the outer surface of the specimen in the vicinity of the failure region. Fig. 3a shows the major strain profile along a section perpendicular to the failure region at several stages for a stretch-bending test using R7.5 mm. The evolution of major strain vs. position at the frame immediately before the specimen fracture, i.e. at stage 429 in this case, is the input data for applying ISO 12004-2. Despite being a material, which underwent a severe PLC effect during straining, the major strain profile at the last stage shows the usual distribution for stretch-bending experiments, enabling the a priori application of the ISO procedure. However, it should be noted that the ISO standard was not developed to deal with a mild or severe stress gradient due to bending [8,11,12]. Therefore, it is expected to provide inconsistent predictions.

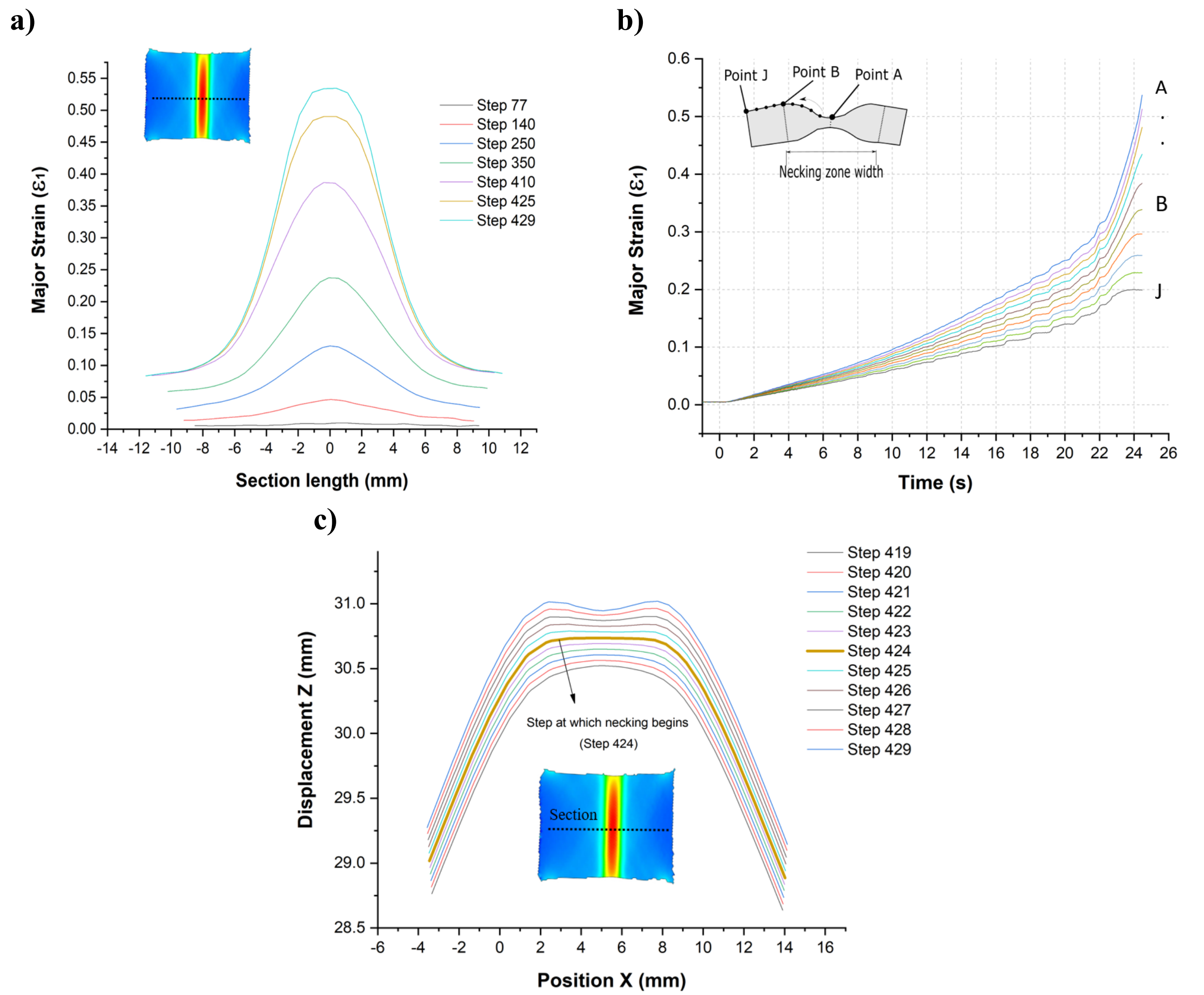

Fig. 3: Different data along a section perpendicular to the failure zone for a stretch-bending tests using R7.5 mm cylindrical punch: a) major strain profile in different step times; b) temporal evolution of the major strain at different points, and c) Z-displacement on the outer surface in different step times.

Fig. 3b depicts the temporal evolution of major strain for a series of points distributed from the fracture site outward along a section perpendicular to the failure region for a test using the R7.5 mm cylindrical punch. Note that these will be the data required for the application of the t-d procedure. Two remarkable facts can be observed. On the one hand, as expected, the curves are relatively separated from the beginning of the test, in agreement with the existence of a severe strain gradient imposed by the punch along the sheet surface. On the other hand, the PLC banding effect is clearly visible, as manifested in the serrated strain curves (see Fig. 3b), leading to significant plastic flow instabilities. This effect is active during most of the test, and seems to reduce its intensity, or even cease, when the plastic instability (necking) begins and develops until the failure of the specimen. At this last stage, the evolution of the strain curves becomes a little bit smoother than in previous frames. However, this material behaviour impact notably the accuracy and the reliability of the time derivatives of the major strain needed for applying the family of t-d methodologies. These methods must be applied carefully and focusing mainly on the last stages to obtain reliable estimations.

For the same test, Fig. 3c shows the evolution in time of the Z-displacement along a section perpendicular to the failure region in different step time until failure. This is the input data required to apply the flat-valley method. As can be observed, a valley that deepens due to the plastic instability process is easily visible in the last stages of the experiment. Moreover, since the processed variables are displacements instead of strains, the curves show a smooth and continuous trend, without noise, independently of the propagation of the PLC band manifested during the plastic straining of the material (see Fig. 3b). As will be seen later, this time and position dependent approach will allow accurate assessing the onset of necking in these materials under stretch-bending states.

Necking prediction using ISO 12004-2:2008

The ISO 12004-2:2008 predictions of major and minor limit strains for both stretch-bending tests, i.e., cylindrical punches of R20 and R7.5 mm, are shown in Table 1. Three specimens have been tested in each case.

Table 1: Forming limit strains predicted by ISO on the outer sheet surface in stretch-bending tests using cylindrical punches of R20 and R7.5mm.

ISO 1200-2:2008 procedure	*Punch R20 mm*		*Punch R7.5 mm*	
	ε_{1lim}	ε_{2lim}	ε_{1lim}	ε_{2lim}
Test 1	0.427	-0.066	0.220	0.051
Test 2	0.424	-0.062	0.307	0.168
Test 3	0.434	-0.061	0.655	0.789

As seen, ISO predictions for the R20 mm punch provide almost identical results for the three experiments performed. In addition, these strain pairs agree with the experimental strain path observed from the DIC, revealing that the process evolved near-plane strain conditions with a slightly negative local strain ratio. However, for the R7.5 mm punch, the results showed a large difference in the necking strains predicted in the three experiments. Moreover, the ISO method estimated positive minor strain values and even minor strains larger than major strains, being completely inconsistent with the experimental strain path around the failure zone. Because the ISO procedure is only tailored for cases with negligible strain gradients, such as Nakazima/Marciniak tests, the predictions for R20 mm are at least consistent. However, when the bending effect becomes severe, e.g., by using a R7.5 mm cylindrical punch, the methodology fails due mainly to the width of the fitting windows proposed in the standard. Similar results have already been discussed by the authors for other metallic materials [8].

Necking prediction using the time-dependent and flat-valley methods

The application of the t-d method requires the first temporal derivative of the major strain evolution in a series of points along a section perpendicular to the final crack, whereas the flat-valley approach makes use of the Z-displacement in a section perpendicular to the failure region at different time instants up to fracture. Fig. 4 depicts both experimental evolutions corresponding to a R7.5 mm stretch-bending test.

The PLC effect exhibited by the material is clearly visible in Fig. 4a. This leads to an unsteady evolution of the strain rate, manifested by repetitive significant increases and a later sudden drops in the strain rate. This peak-shaped evolution evolves at the different points during the test, experiencing increasing peak amplitudes as the plastic strain increases. Nevertheless, as mentioned before, this effect seems to saturate in the last stages, reducing its intensity, and allows one to observe the usual trend in a necking-controlled failure. This means that differences in the evolutions of the points within and outside the necking region can be identified by analyzing only the last frames (see the square box in Fig. 4a).

This existing noise during mathematical computation makes very difficult to accurately determine the necking zone width and the necking time (steps 1 and 2 numbered in the t-d method session), involving, respectively, the selection of the last point that reaches a zero-strain rate at fracture and the time instant (marked as $t_{necking}$ in Fig.) at which the strain rate at the boundary of the instability region reaches a local maximum. Therefore, the t-d method must be applied very carefully to obtain reliable limit strain estimates.

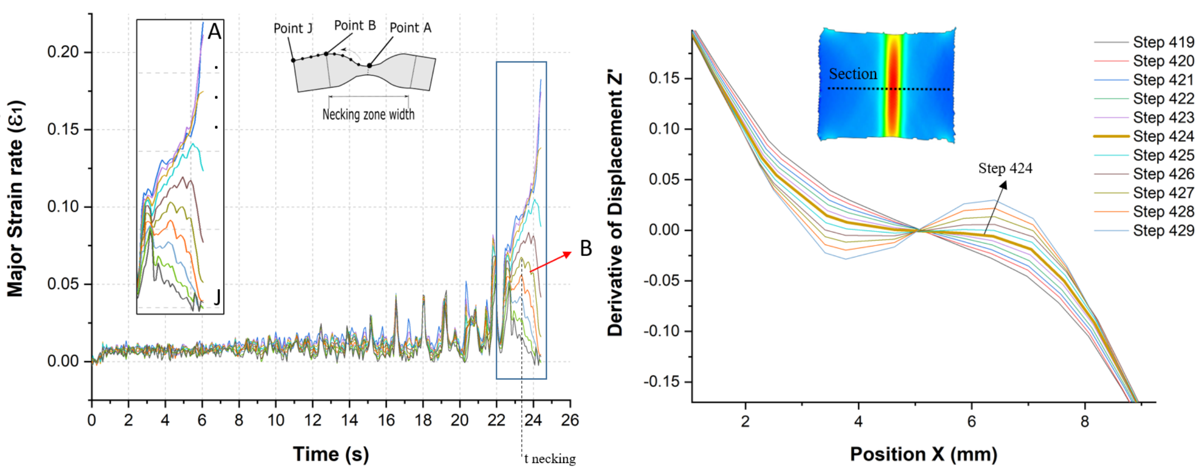

Fig. 4: Evolution of a) the first temporal derivative of the major strain at several points along a section perpendicular to the fracture region and b) the Z-displacement rate in a section perpendicular to the failure region at different step times for a R7.5mm stretch-bending tests.

On the other hand, as expected in the light of experimental data shown in Fig. 3c, the flat-valley method provides a straightforward, objective, and direct approach, since the first spatial derivative of Z-displacement shows a smooth and a noise-free trend (see Fig. 4b).

In this method, the onset of necking is established at the step time at which the slope in the spatial derivative of Z-displacement in the plastic instability zone remains constant (not necessarily null), in other words, when this curve becomes flat (identified as step 424 in Fig.). This points out that methodologies based on direct local observation of Z-displacements, such as the flat-valley method, allow an accurate estimate of the onset of necking in PLC-driven material. The flat-valley method, developed and tested for both Nakazima and stretch-bending tests [8], provides an easy and practical alternative to assess the formability in materials that exhibit the PLC phenomenon. In this work, its predictions are considered a base line to compare the rest of the methods.

Table 2: Forming limit strains predicted by the t-d method on the outer sheet surface in stretch-bending tests using cylindrical punches of R20 and R7.5 mm.

t-d method	*Punch R20 mm*		*Punch R7.5 mm*	
	ε_{1lim}	ε_{2lim}	ε_{1lim}	ε_{2lim}
Test 1	0.386	-0.074	0.421	-0.038
Test 2	0.397	-0.074	0.431	-0.038
Test 3	0.389	-0.073	0.415	-0.038

Table 3: Forming limit strains predicted by the flat-valley method on the outer sheet surface in stretch-bending tests using cylindrical punches of R20 and R7.5mm.

flat-valley method	*Punch R20 mm*		*Punch R7.5 mm*	
	ε_{1lim}	ε_{2lim}	ε_{1lim}	ε_{2lim}
Test 1	0.394	-0.075	0.469	-0.039
Test 2	0.379	-0.075	0.484	-0.039
Test 3	0.386	-0.073	0.489	-0.039

Table 2 and Table 3 show the predictions of strain limits using the t-d and flat valley methods, respectively, for the cylindrical punch stretch-bending tests R20 mm and R7.5 mm. Again, three specimens were tested for each punch radius.

As can be seen, the predictions of both methods for the R20 mm punch are almost coincident, whereas for the R7.5 mm test, the t-d method slightly underestimates the material formability with respect to the flat-valley results, used as reference, due to the difficulties previously discussed associated to the plastic flow instabilities in PLC materials. Generally, the highest difference in mean values was around 14% for the R7.5 mm punch. It can be said that the estimation by both methodologies shows a remarkably small dispersion.

Compared with the ISO standard, although the ISO predictions in the case of smooth strain gradient tests, that is, R20 mm cylindrical punch, slightly overpredict with reference values and yield differences of about 11%. Therefore, it becomes evident its inability to assess the formability limits in cases of severe strain gradient tests, in our case, the R7.5 mm cylindrical punch. As mentioned above, this limitation is related to the fact that this standard was tailored to tests with negligible bending effect (Nakazima/Marciniak tests) and not directly to the fact of the existence of the PLC phenomenon.

Conclusions

In this study, the formability of a 2.94 mm thick AA5754H11 PLC-driven material is analysed in two different stretch-bending tests using cylindrical punch radii, one R20 mm that generate a smooth/mild strain gradient in the sheet, and another of R7.5 mm, which induces a much severe one. Various necking detection techniques, particularly ISO12004-2:2008 [7], and the time-dependent and flat valley methods proposed in the literature [8], have been employed to obtain and discuss their predictive capabilities to assess the necking limit strains. The primary outcomes of this study are the following:

- ISO 12004-2:2008 is not able to estimate the necking limit strains under mild or severe stretch-bending conditions.

- PLC-driven materials exhibit significant instability during their plastic deformation and necking development, being not conducive to the application of time-dependent detection methods of necking.
- In general, time-dependent methods, based on the analysis of time derivative of strains, for instance, must be applied very carefully to obtain reliable estimations.
- Local curvature evaluation methods, such as the flat-valley method, seem to be the most suitable to assess the onset of necking in these materials and severe stretch bending conditions.

A more extensive systematic study, using different punch radii, is being carried out to corroborate the previous conclusions more accurately.

Acknowledgements
The authors acknowledge the funding provided by Grant PID2021-125934OB-I00 financed by MCIN/AEI/10.13039/501100011033 and by ERDF "A way of making Europe" (EU). The collaboration of the BSc student Bruno Cruz Luque is also acknowledged.

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