Characterisation of Inhomogeneous Plastic Deformation of AlMg Sheet Metals During Tensile Tests

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Abstract. The Portevin-Le-Chatelier (PLC) effect was analysed quantitatively in the selected AlMg alloys with Mg-content between 2,8-4,6%. The propagation and characteristics of PLC bands were detected by digital image correlation (DIC) technique and the parameters of the bands were evaluated from strain distributions of tensile test specimens. In parallel, stress-strain curves were analysed evaluating stress serrations. The numerically defined parameters of changes in stress and strain were used for characterising the PLC effect on the behaviour of different sheet metals. General statements of literature were numerically proven for the tested materials and the effect of magnesium content on stress amplitude was analysed in detail.

1. Introduction

It is well known from the literature and experiments that stress oscillations – serrations – can be observed during tensile tests in AlMg alloys. Serrations are defined as sudden stress drops or strain jumps in the stress-strain curves of certain metals. The deformation mechanism in these alloys is known as the Portevin-Le-Chatelier (PLC) effect [1] and it is derived from dynamic strain aging (DSA) which is the repeated action of diffusing-solutes which pin the dislocations. As the stress increases, dislocations break free from this pinning [2-5]. On the macroscopic scale, this phenomenon is observed as strain localization in the form of narrow bands of intense shear [6]. The deformation bands leave undesirable traces on the surface of the sheet product during forming operations, thus restricting the application of AlMg alloys for car outer body panels. In addition, the PLC effect is harmful for formability because the PLC bands can lead to a premature onset of necking and fracture [7].

According to the literature, serrations are usually divided into three types: Type A, B and C [3,8]. The main characteristics of serrations can be defined from tensile test diagrams. The first serration can be observed at εc critical strain after the onset of plastic deformation. The amplitude of serrations can be characterised by Δσ. The frequency spectrum of serrations also provides useful information for characterising the PLC effect which can be evaluated from normalized stress amplitude diagrams by fast Fourier transformation (FFT) [9, 10]. The serration parameters are influenced by the tensile strain (ε), the strain rate (ε̇), the testing temperature (T), the grain size of the alloy (d) and the dimensions of the specimen (aspect ratio and thickness). The effects of the parameters are the following:

- The increase of strain during tensile tests increases Δσ stress amplitude, modifies stress drops from types A to B and C. This indicates that DSA is becoming more significant, as the strain increases [8].
• As function of the strain rate, the critical strain first shows a decreasing tendency, then reaches a minimum value and finally increases. The serration amplitude decreases as the strain rate increases [8, 11, 12].
• As the temperature increases – similarly to the strain effect – the strain amplitude increases and the stress drop type changes from A to B and later to C [8].
• Increasing the grain size decreases Δσ in case of AlMg alloys.
• The stress-drop size was found to slightly decrease with increasing the specimen thickness. The cross-section form factor of the specimen also influences Δσ, from a circle to a rectangular shape, Δσ slightly increases [10].

It is obvious that serrated yielding in AlMg alloys is influenced by the Mg-content and heat treatment as presented in [13]. Comparing AA5052 and AA5182 alloys higher stress drops occurred on the stress-strain curve of AA5182 alloy and serrations showed a higher rate than in case of AA5052 alloy.

Further analysis of the PLC effect is based on techniques which show the local strains of specimens during tensile tests. Namely, these are the digital image correlation (DIC) methods [4, 6, 10, 15, 16, 17] and laser speckle techniques [14]. Using the graphic representation of the strain field or its numeric results, all characteristics of PLC bands can be detected and evaluated such as the band strain, the width and the velocity of the band front edge.

However, it should be mentioned that the exact definition of PLC band parameters is missing from the literature, although many publications deal with them. For example, the PLC band strain (εPLC) is an extent of the incremental strain according to [4] or the strain difference between the internal and external band strain [6]. Some authors suppose that the base strain is zero which can be found in strain curves in publications [14, 16, 17]. In [17] the width of the PLC band is defined from the strain-length function at half-height and εPLC is given as the maximum strain of the peak.

2. Experimental procedure
The experiments were focusing primarily on AlMg3 sheets but some tests were carried out on AlMg4,5 alloys for comparison. Table 1 shows the thickness and chemical composition of the sheets.

| Table 1. Basic data of the tested sheets |
|-----------------------------------------|
| Thickness (mm) | Mg (wt.%) | Fe (wt.%) | Si (wt.%) | Mn (wt.%) |
| A1 | 1.5 | 2.82 | 0.23 | 0.15 | 0.34 |
| A2 | 2.5 | 3.30 | 0.11 | 0.05 | 0.33 |
| A3 | 2.5 | 3.41 | 0.23 | 0.17 | 0.16 |
| A4 | 2.5 | 3.52 | 0.27 | 0.13 | 0.16 |
| A5 | 1.25 | 4.57 | 0.28 | 0.13 | 0.22 |
| A6 | 1.5 | 4.69 | 0.11 | 0.09 | 0.25 |

A2 and A3 sheets were tested both in annealed (O) and cold rolled (H22) condition. The received sheets were cold rolled and subsequent annealing was carried out at 320 °C/2 hours. The sheets were tested in rolling (RD), transversal (TD) and diagonal (DD) directions.

2.1. Evaluation of the DIC measurements
The time series of the strain fields of the tensile test specimens were recorded by GOM ARAMIS [18] hardware-software system. Graphic representation of the strain distribution was available in colored images with scale bars. The GOM Inspect software offered digital output of measured strain values along straight lines parallel with or perpendicular to the tensile axis. Evaluation of strain fields was carried out from 2 to 15% global strain by 1...2% strain increments. From one strain matrix the following parameters were calculated: the average strain εAVG (which is equal to the global strain measured by extensometer); the standard deviation of strains εSTD; the maximum and minimum values of the strain matrix εmax and εmin; the strain distribution (histogram) characterized graphically and approached by a four-parameter Gaussian function.
Figure 1 shows the graphic evaluation of a PLC band. The band width (b) is calculated from the distance of dashed lines and the angle between the tensile axis and the border line is given by $\phi$. The absolute band strain is estimated from the color scale as 7.2% but according to the former definition, PLC strain is the increment of the internal and the external strain. The external strain is marked by green which might be ~6.5% (this is similar to the global strain measured by the extensometer) – so $\varepsilon_{\text{PLC}}$ is calculated to 0.7% which is $\approx 0.007$ in logarithmic strain. This estimation shows that a better definition can be given for the PLC strain if the average (or global) strain along the test line is the basis and the increment is related to that value.

Digitized strain values collected from the specimen center line can be seen in Figure 2 together with a colored strain map. The first impression is, as more PLC bands are on the specimen, their width and maximum strain strongly differs from each other, as they are in different phases of band propagation. This is why a uniform definition of band parameters is not possible. Two alternatives can be offered for evaluation: (i) one characteristic band is selected for evaluation, or (ii) considering that the strain is a random variable, some statistical measurements should be implemented for characterization of band parameters.

Observing the band on the right side of the specimen (Figure 2) the first question is band width. It can be defined as the intersection of the strain graph with the average strain line (marked with red) or with the line above it (marked with green) – for example at half height of the band. It is suggested by the authors of this paper that band width should be defined as the intersection with the average strain line. The second question concerns band height, which might be the strain maximum or a characteristic average strain. The actual band height is 7.07% and the average strain is 6.55% – resulting that $\varepsilon_{\text{PLC}}$ is 0.52%. Regarding the peak on the left side (at L=27.6 mm), the strain maximum is 7.25% and the PLC strain is 0.7%, which is the same as $\varepsilon_{\text{PLC}}$ evaluated from the graphic image in Figure 1.

The referenced authors suggest a global parameter for the characterisation of the average PLC strain. This might be the average of the strain values above the $\varepsilon_{\text{AVG}} + \varepsilon_{\text{STD}}$ line (in green). This is a bit lower than the maximum strains (7.01%) but more balanced than the value of one individual peak. For example, this average can be compared with the average of the five highest peaks. From that it follows that the values are very similar – in the first case $\varepsilon_{\text{PLC}} = 7.01 - 6.55 = 0.46\%$ while the average of the five peaks is 0.48%.

The average band width can be calculated from the sum of intersections where the strain is equal to the average – now it is 36.8 mm and the number of bands is six so $b_{\text{AVE}} = 6.13$ mm.

A possible characterisation of inhomogeneous local deformations during tensile tests is suggested by [19] which is independent from the PLC effect and valid for any kind of inhomogeneity and allows...
to compare the strain fields of different materials. The so-called local inhomogeneity factor, $\Lambda$ can be calculated with the following equation:

$$\Lambda = \frac{\varepsilon_{\text{max}} - \varepsilon_{\text{min}}}{\varepsilon_{\text{AVG}}}$$  \hspace{1cm} (1)

This parameter is dependent of global strain, $\Lambda$ is the function of $\varepsilon_{\text{AVG}}$.

2.2. Evaluation of serrations from tensile test diagram

A typical true stress-time diagram is illustrated in Figure 3. Fitting a four-parameter Voce-equation on the measured data stress amplitudes can be evaluated as the differences of the measured data and the calculated curve points. Figure 4 shows that type A serrations can be identified between 35 s and 45 s and later high-frequency B-type serrations occur with C-type stress jumps. The strain amplitude is increasing versus time.

![Figure 3. Stress-time diagram, approximated by Voce equation.](image)

![Figure 4. Stress amplitudes versus time (\(\dot{\varepsilon}=0.0022 \text{ 1/s})\).](image)

As strain amplitude is a random variable, statistical evaluation is needed for calculating the serration parameters. For one approach, the referenced authors suggest to follow the evaluation method similar to surface roughness – that means to calculate average stress amplitude analogue to $R_a$ and maximum amplitude $R_z$. The new parameters will be designated as $\Delta \sigma_a$ and $\Delta \sigma_z$ respectively and they can be calculated according to equation (2).

$$\Delta \sigma_a = \frac{\sum_{i=1}^{n} \text{abs} (\Delta \sigma_i)}{n} \text{ and } \Delta \sigma_z = \left[ \left( \sum_{i=1}^{5} \Delta \sigma_{i,\text{max}}^+ \right) - \left( \sum_{i=1}^{5} \Delta \sigma_{i,\text{max}}^- \right) \right] / 5$$  \hspace{1cm} (2)

Another approach is the distribution analysis of the serrations. The absolute values of the stress amplitudes are illustrated in a relative density histogram (Figure 5).

![Figure 5. The Weibull distribution of the serrations. The points refer to measured probability values while the lines illustrate the calculated probability density and cumulative distribution functions.](image)

The shape of the point arrangement refers to the Weibull distribution, which was validated by regression parameters. Dozens of calculations have proven that $R^2$ is near to 1 and always over 0.96 – so the hypothesis is acceptable. Using these Weibull functions the stress amplitudes can be calculated.
for different probabilities. Three values were tested and evaluated: \( p = 0.97; 0.98 \) and \( 0.99 \). It was concluded that \( \Delta \sigma_p \) is stable at \( p = 0.97 \) and this parameter correlates well with \( \Delta \sigma_z \).

3. Results and discussion

3.1. Results of DIC measurements

The strains defined in point 2.1. are illustrated in Figure 6 and 7. Figure 6 shows the comparison of maximum strain values, the calculated average strain plus twice the standard deviation \( \epsilon_{AVG + 2\epsilon_{STD}} \) and the PLC peak strain, which is the average of the strain values above \( \epsilon_{AVG + \epsilon_{STD}} \). The horizontal axis contains the global or average strain, its points were detected at selected moments of the tensile test.

\[ \epsilon_{PLC} \approx \epsilon_{MAX} - \epsilon_{AVG} \]

It follows from Figure 6 that for the first approach the maximum strain values \( \epsilon_{MAX} \) and \( \epsilon_{AVG + 2\epsilon_{STD}} \) are very similar to each other and do not differ significantly from the evaluated average PLC peak strains. For easier evaluation of strain maps maximum values can be used also as the characteristic strain for evaluation of the PLC strain increment: \( \epsilon_{PLC} \approx \epsilon_{MAX} - \epsilon_{AVG} \). Figure 7 illustrates the PLC strain, which is calculated as the difference of the PLC peak strain minus the average strain – by definition it is the strain increment caused by the PLC effect related to its environment. The measured values show an increase as the global strain increases \([4, 6, 8]\). A further conclusion is that the annealed sheet exhibits higher PLC strain than the cold rolled one.

The local inhomogeneity factor (\( \Lambda \)) can also be calculated from the points of maximum and minimum strain values as the function of the global strain. The slope of linear fit to maximum and minimum strain values \( \epsilon_{MAX} \) and \( \epsilon_{MIN} \) have to be evaluated, and their difference gives \( \Lambda \). Similarly plotting the \( \epsilon_{PLC} \approx \epsilon_{MAX} - \epsilon_{AVG} \) points versus the average strain (Figure 7) the slope of the fit line characterises the material behaviour as a global parameter of the PLC strain increment.

\[ \Lambda = \frac{\epsilon_{MAX} - \epsilon_{MIN}}{\epsilon_{AVG}} \]

Figure 7. PLC strains as function of the global strain

Figure 8. Comparison of sheets by their PLC strain increment
The comparison of the two different AlMg3 alloys is illustrated in Figure 8. As can be seen from Table 1, the A2 sheet contains 0.11% Fe while the A3 has 0.23%. Therefore the volume of intermetallic particles in alloys are respectively 0.53% and 1.35% which means that the formability of the A2 sheet is better than that of the A3 alloy. The slopes of PLC strain increments show this effect very clearly as values are lower in case of the A2 sheet. Similar results can be found in [6]. Another important observation is that inhomogeneity parameters of cold rolled H22 sheets are lower than annealed ones (see Figure 7).

Band velocity can be measured easily using DIC technique. Figure 9(a) shows a typical A-type band which develops continuously from one end of the tensile specimen to other. Knowing the geometric dimensions, the band displacement can be estimated from the strain maps as the function of time.

![Figure 9. Map of the PLC band (a) and the band velocity versus the global strain (b)](image)

Figure 9(b) contains the detected points of band velocity in rolling, diagonal and transverse directions and the power function which was fitted to all points. Both the shape of the function and the measured band velocities are in accordance with [5].

The average band width was calculated two ways, (i) from the sum of intersections where strain is equal to the average ($\varepsilon_{AVG}$) or (ii) from intersections with the $\varepsilon_{AVG} + \varepsilon_{STD}$ line, which was formerly used for calculation of the average band strain as well. Band widths do not show regular tendency as the function of the global strain at the tested strain rate ($2.2 \times 10^{-3}$/s), therefore their average was calculated between 5-15% strain range in case of the A2_H22 sheet. The band width evaluated from the intersections of $\varepsilon_{AVG}$ line is 7.18 mm while evaluated from the $\varepsilon_{AVG} + \varepsilon_{STD}$ line the width is smaller, only 3.88 mm. Having studied the strain distributions equation (i) is more realistic, as it is in accordance with the basic value of the PLC strain increment while using equation (ii) approximately half of the bands were not intersected with the higher line. At a certain moment bands along the specimen are in different phases of propagation and this explains why their band strain and width is different. Another factor is that the type of serrations changes as global strain increases.

3.2. Results of serration analysis

Figure 3 and 4 show typical stress-time functions and stress amplitudes. Average and maximum amplitudes can be obtained by evaluating the stress amplitudes in 5 s time intervals according to equations (2). These are illustrated in Figure 10 for A2_H22 sheet. Both parameters are increasing versus time and obviously versus strain.

It is also clear that the maximum stress amplitude ($\Delta\sigma_z$) varies more significantly than the average ($\Delta\sigma_a$), this is why the former parameter will be used during the following evaluations, together with ($\Delta\sigma_w$) which is calculated from the Weibull-distribution of the stress amplitudes. Figure 11 illustrates the plot of amplitudes derived from the Weibull-function at p=0.97 and from 5-5 positive and negative stress peaks.
Considering the common character of Figure 7 and 10 – namely both the PLC band strain and the stress amplitude increases as the function of the global strain – it follows that close correlation exists between the PLC band strain and the stress amplitudes. It is illustrated in Figure 12, where the PLC band strains were calculated at the given global strain points while the stress amplitudes were evaluated from the neighbouring stress-strain values. The mechanical background of this correlation is explained by the sudden PLC strain increments which cause stress drops. The amplitude of serrations is influenced by the magnitude of strain increments and by the global stiffness of the testing machine-specimen system.

For characterising the serration behaviour of one sheet metal authors suggest to evaluate the formerly defined stress amplitude parameters between 8% and 12% global strain – similarly to plastic anisotropy. This strain domain represents the steady-state process of serrations and its position is approximately in the middle of the uniform elongation area. Having collected the stress amplitude parameters of the tested materials in rolling, diagonal and transversal directions the average of the measured points are displayed in Figure 13 as the function of the magnesium content (Mg%). As the graph shows a relative close correlation exists between the stress amplitudes and the Mg-content, as it is published in [13] for AA5052 and AA5182 alloys. This can be explained by the interaction of Mg atoms and dislocations – the higher the magnesium content, the more obstacles occur and DSA becomes more effective. Increased DSA activity causes stronger band propagation and increases the differences between stress peaks and drops.
4. Summary and conclusions
The PLC band attributes and the stress serrations were numerically characterised using newly defined parameters for strain inhomogeneity and stress oscillations. In both cases a statistical approach was used for better evaluation of random variables. The PLC band parameters were measured and gained from DIC measurements. The strain distributions were characterised by their average, standard deviation and minimum-maximum values.

The global characterisation of a selected sheet metal is possible using the graphs of global strain and PLC strain increment. The slope of the fitting line is a numerical parameter of strain inhomogeneity caused by the PLC effect. It was concluded from the measurements that the formability of sheets can be characterised by this parameter, the lower the slope, the better the formability. It can also be declared that cold forming lowers strain inhomogeneity.

The evaluation of serrations was carried out applying similar statistical methods. The absolute values of stress amplitude distribution over a given strain interval was approached by a two-parameters Weibull distribution and 97% probability value was used for the definition of the stress amplitude. It has been proven that strong correlation exist between the Mg-content and the stress amplitude. Another important observation is that the PLC band strain and the stress amplitude increase together.

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