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PLC Effect at Different Types of Loading During Static Tensile Testing of Aluminium Alloys

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Abstract: Aluminium and aluminium alloys are indispensable materials nowadays, widely used in various constructions. It is known that some aluminium alloys, such as Al-Mg, show inhomogeneous, localized deformation phenomena at certain temperatures and strain rates. This is known in the literature as the appearance of Portevin-Le Chatelier lines, or short the PLC-effect. The Portevin-Le Chatelier effect contributes to the reduction of material ductility and leaves surface defects on the final products. The study of this phenomenon was carried out using a static tensile test and the digital image correlation method. The influence of using a constant increase of stress on the phenomenon itself was studied in comparison to the classical control of the testing machine with a constant crosshead speed. The results of the study show that the phenomenon persists regardless of the type of control and no significant changes were observed at used testing parameters. Regardless of the deformation parameters, PLC lines form throughout the whole duration of the plastic deformation until the specimen breaks.

Keywords: Al-Mg alloy, DIC, PLC effect, constant stress increase

1. Introduction

Due to their low density, weldability, corrosion resistance, and good thermal and electrical conductivity, aluminum and aluminum alloys are widely used in various constructions [1]. Al and Al-alloys also have extremely good ductility, as a result of which it is possible to shape them with different forming technologies, and to achieve shapes that cannot be produced from steel.

According to the European standard EN 573-3:2002, aluminum alloys are divided into alloys for plastic processing and casting alloys. They are further divided according to the method of hardening into heat-hardening (precipitation hardening) and heat-nonhardening alloys (cold deformation hardening) [2-4].

Al-alloys for plastic processing are the 5xxx and 6xxx series, where the main alloying element in the 5xxx alloy series is magnesium, and in the 6xxx series magnesium and silicon. The disadvantages of these alloys are well known, such as microsegregation and porosity, which can be reduced by homogenization annealing, additional alloying and processing of the melt. 5xxx series Al-Mg alloys for plastic processing are most often produced by casting blocks using a direct casting process, which are later subjected to rolling, pressing, extrusion, etc. [5-6].

Research has established that at some of Al-alloys from 5xxx series, during cold plastic deformation, regardless of previous technological processing, localized deformations associated with the Portevin-Le Chatelier (PLC) effect occur [7-10]. The PLC effect manifests itself on stress-strain diagrams during static tensile testing as a specific serration of the curve with sudden changes in stress, Figure 1.

This phenomenon was first documented by F. Savart during his research on copper alloys, however, a more significant contribution to the understanding of this

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phenomenon was made by the research of Francois Le Chatelier and Albert Portevin on duralumin [11]. Therefore, this phenomenon of plastic instability is called Portevin-Le Chatelier, or PLC-effect.

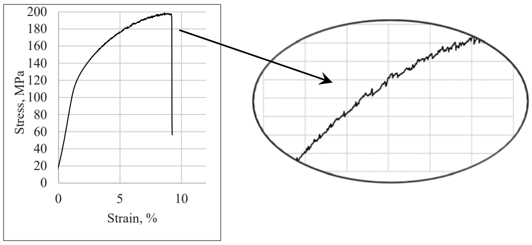

Figure 1: Stress–strain curve with PLC effect at constant crosshead speed 10 mm/min.

Studies indicate that this phenomenon occurs primarily due to the presence of dissolved elements in the alloys and that instability of the plastic flow occurs in a certain range of temperature and strain rate, more precisely when the overall sensitivity to the strain rate becomes negative [10-12].

Numerous studies have been carried out on different alloys on which this phenomenon is observed, and it has been established that the occurrence of the PLC-effect is influenced by various factors such as crystal orientation, dislocation density, dispersion of particles in the material, etc. Depending on the type of alloy and test parameters, it has been established that there are different types of PLC lines. They are classified as lines of type A, B, C, where D and E types of lines occur less frequently [12-15].

The most prominent feature of the PLC effect is localized deformation in a certain part of the deformation zone and its movement along the zone with an increase in applied stress. In order to better understand and visualize this phenomenon, the digital image correlation method (DIC) is often used. Localized deformation, i.e. PLC lines, is visualized by the DIC method as lines of different colors depending on the amount of achieved deformation.

PLC lines can be up to several millimeters thick, and extend at an angle of approximately 55° in relation to the direction of stretching of the samples. Lines can move through the sample in different ways, depending on the place of generation and the direction of propagation, Figure 2.

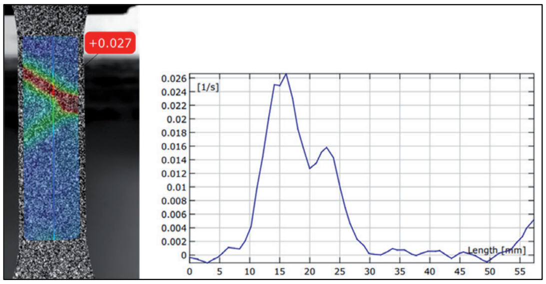

Figure 2: DIC representation of PLC lines in an Al-Mg alloy sample with line width measurement.

The aforementioned localized deformation leaves a negative impact on the mechanical properties, leads to a decrease in ductility, increased risk of brittle fracture, increase in tensile strength, etc. [14,16]. In addition to the above, the phenomenon also causes a certain roughness of the finished products surface, which represents a certain disadvantage in the field of application where a final product with a high gloss surface is required [16].

Whether PLC lines will be formed and which type of line will be formed, depends on the processing parameters. One of the most influential parameter is the strain rate. As mentioned, PLC-effect occures only in certain ranges of strain rates, depending on the type of processed alloy [12,14-16].

Most of the research on this phenomenon was carried out using static tensile testing, with the application of other methods such as DIC, thermography and the acoustic emission. It is unique to all of them that they use classic control of the testing machine with a constant crosshead speed. The question arises what if the displacement control method is changed for the test?

Research within this paper investigates the effect of changing the displacement control of the static tensile testing device. It was investigated how, the control of testing machine with constant increase of stress instead of the classic control with constant crosshead speed, affects the occurrence of the PLC effect in the Al alloy EN AW -5083 (AlMg4,5), with the occurrence of PLC effect.

2. Experimental Section

Static tensile tests were carried out on the aluminum alloy EN AW -5083 (AlMg4.5), which has the appearance of the PLC-effect. The tests were carried out on a Hegewald & Peschke Inspekt table 100 static tensile testing machine, Figure 3, using the associated control program.

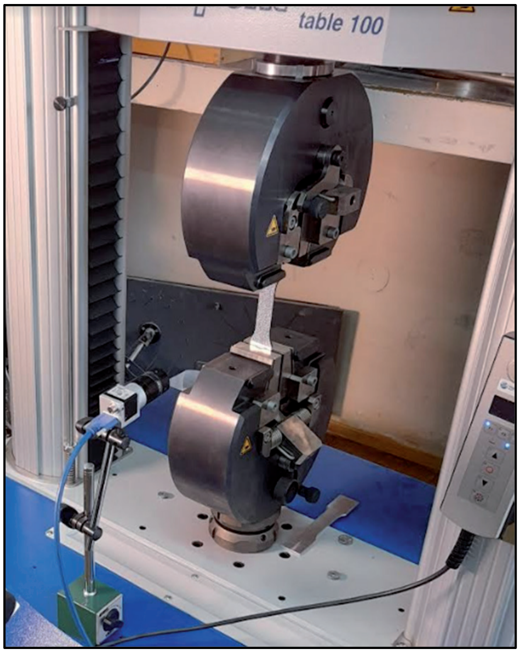

Figure 3: Specimen in the grip and position of the digital camera during the static tensile test.

Simultaneously with the static tensile test, the deformation of the samples was recorded with a digital camera for the subsequent 2D DIC method of displacement analysis and determination of deformation localization. The recording frequency of the digital camera was 10 images per second (10Hz). GOM CORRELATE 2020 software package was used for DIC analysis. Rectangular samples with a thickness of 3 mm were made by CNC processing. The dimension of the measuring area of the samples was 55 x 20 mm. The surface of the samples was adequately prepared by applying random markers, necessary for subsequent DIC analysis, Figure 4.

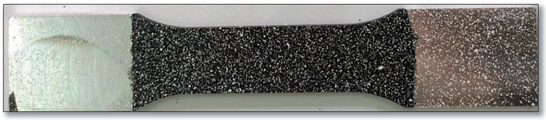

Figure 4: Sample with applied markers for DIC analysis.

In order to investigate the influence of changing the device control mode for the static tensile test on the appearance of the PLC-effect, tests were performed at two different constant crosshead speed, which served as a reference result. After that, the control was changed in such a way that the device applies a constant stress increment, also with two different stress increment values, Table 1.

Table 1: Control parameters.

Constant crosshead speed [mm/min]	*Constant increase of stress [MPa/s]*
10	5
50	10

The results of the static tensile test and subsequent DIC analysis are presented in the section results and discussion. From the aforementioned analyses, the impact of the change in device control on the appearance of the PLC-effect was observed and conclusions were drawn.

3. Results and Discussion

During the testing of the samples, the stress-strain curves were continuously recorded, and the deformation of samples surface was recorded with a digital camera for the subsequent analysis of deformation localization using the DIC method. The recorded stress-strain diagrams are shown in Fig. 5.

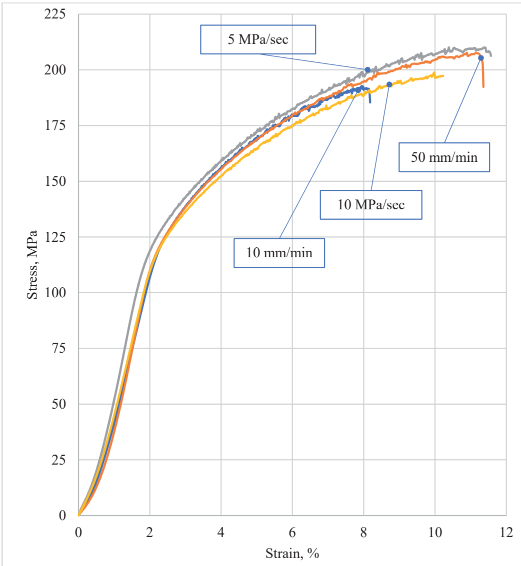

Figure 5: Stress-strain curves at constant crosshead speed and constant increase in stress.

From the obtained stress-strain curves, it can be seen that during plastic deformation, until fracture of samples, there is a certain serration curve with oscillation in measured stress. This is associated with the presence of the PLC-effect in the tested alloy. From the recorded curves, it is clearly visible that regardless of the change in the testing parameters, there is no change in the appearance of the stress curves. All recorded curves have a clearly visible stress oscillation during the experiment, which indicates the formation and propagation of PLC lines. It can be concluded that the change of machine control and the use of constant stress increment during testing, does not affect the appearance of the curve on stress-strain diagram for tested alloy.

From the analysis, it is evident that the instability in the stress-strain curve occurs immediately after the beginning of the plastic flow of the material. The instability itself is uniform throughout the whole deformation process and lasts until the samples break. It can be clearly seen from the presented stress-strain diagrams that there is no characteristic point of Ultimate Tensile Strength (or UTS) on the curves, the max. stress is measured at the fracture point.

Furthermore, DIC analysis was performed on all tested samples, first to visualize the presence of the PLC phenomenon, and later to determine the impact of changing the device control mode for the experiment. Figure 6 shows the typical formation and propagation of PLC lines in one sample at the indicated times.

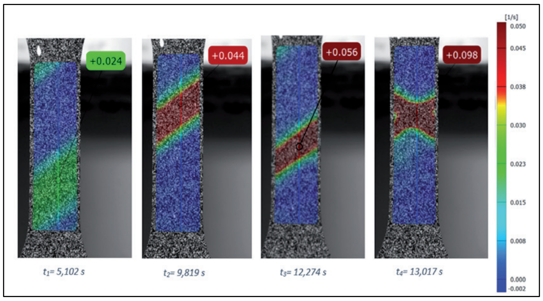

Figure 6: DIC display of PLC lines at constant crosshead speed of 50 mm/min.

Below are the results of the quantitative DIC analysis of the strain rate changes during the appearance of PLC lines, Figure 7. Diagrams were recorded at all testing conditions in order to determine possible changes in the behavior of PLC lines depending on the used testing parameter.

By comparing the obtained strain rates from DIC analysis, it can be seen that as the crosshead speed increases, the strain rate also increases as expected. When using a constant stress increment, an increase in the strain rate is also observed during increase of the stress increment amount.

When comparing the static tensile test, Figure 5, and DIC analysis, Figure 7, it is clear that changing

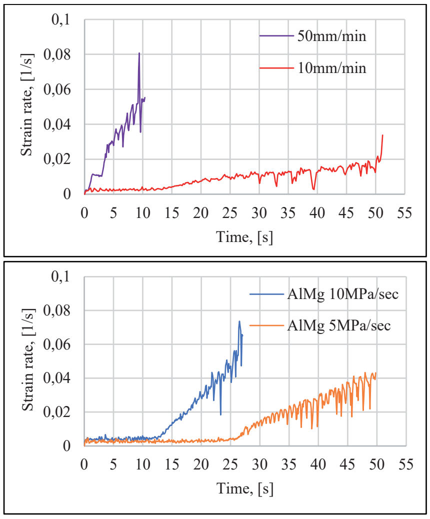

Figure 7: DIC analysis of strain rates at: a) constant crosshead speed, b) constant increase in stress.

the device control mode does not lead to the absence of the PLC effect at tested alloy. Moreover, it can be observed that when controlling with a constant stress increase, there are more pronounced oscillations in the strain rate of the localized deformation. Those oscillations and sudden drops in strain rate are probably related to the formation of PLC lines, which needs further investigation.

From these comparisons, it can be concluded that regardless of the method of controlling the device, using a constant crosshead speed or a constant increase in stress, under all the conditions used, PLC lines are formed and gradually deform the test part of the samples.

4. Conclusions

Research was done on the effect of changing the displacement control of the static tensile testing device to the control with constant increase of stress, on the occurrence of the PLC effect in the Al alloy EN AW-5083.

From the obtained data and performed analysis it is clear that EN AW-5083 Al alloy has occurrence of PLC effect during static tensile testing. Changing the control of tensile testing machine to constant increase of stress does not lead to the absence of the PLC effect because in both cases PLC lines appear.

The observed peaks in the strain rate by DIC analysis are probably related to inhomogeneous deformation, but this needs to be confirmed by additional research.

Acknowledgments

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