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Original scientific paper

INVESTIGATION OF THE PORTEVIN-LE CHATELIER EFFECT IN AlMg ALLOYS: EFFECT OF TESTING RATE

Ivan Jandrlić, Lorena Mrkobrada

Faculty of Metallurgy, University of Zagreb, Sisak

ABSTRACT

The study investigates the Portevin–Le Chatelier (PLC) effect in the cold-rolled Al-Mg alloy EN AW-5754. The tensile tests were performed on dog bone specimens at test speeds of 10, 20, and 50 mm/min. Digital image correlation (DIC) and infrared thermography were used to monitor strain rate and temperature changes. The results showed a strong correlation between PLC line propagation, strain rate variations, and temperature changes. Regardless of the test speed, the characteristic jagged shape of the material was observed due to the PLC effect. As the deformation progressed, both the strain rate and the temperature increased, with the changes being more pronounced at higher test speeds. DIC and infrared images show that temperature peaks correspond to moments of increased plastic deformation and sudden drops in strain rate. The formation of overlapping PLC lines also showed the random and unpredictable nature of the phenomenon.

Keywords: AlMg alloy, Portevin-Le Chatelier effect, testing rate, Digital Image Correlation (DIC)

Corresponding Author:
Ivan Jandrlić,
Faculty of Metallurgy, University of Zagreb
Aleja narodnih heroja 3, Sisak, Croatia
Tel.: +385 44 533 378
E-mail address: ijandrli@simet.hr

1. INTRODUCTION

The Aluminum alloys of the 5xxx series, which primarily contain magnesium as the main alloying element, are highly valued in the automotive industry due to their excellent strength-to-weight ratio, corrosion resistance, weldability, and formability [1, 2]. These alloys are increasingly used in the automotive industry, especially in body construction, where their ability to reduce vehicle weight and fuel consumption is crucial [2]. Due to their corrosion resistance, low weight, hardenability, and high recycling potential, aluminum alloys are widely used in various industries [3]. The addition of magnesium improves the strength of these alloys through hardening, which occurs when dislocations interact with each other or with precipitates of dissolved elements and different phases [2, 4]. As a result, the AlMg alloys of the 5xxx series are prone to unstable plastic flow under certain deformation conditions. This unstable flow manifests itself in the form of the Portevin-Le Chatelier (PLC) effect, which causes localized deformation that often occurs in the form of deformation bands [5].

The PLC effect causes the formation of localized deformation bands, which manifest as repetitive serrations in the stress-strain curve during tensile testing [6, 7]. Depending on the nature of serrations, three main types of deformation bands A, B, and C are formed, the appearance of which is influenced by the strain rate and temperature (Figure 1). In some cases, rarer deformation bands such as types D and E have also been reported in the literature [8, 9].

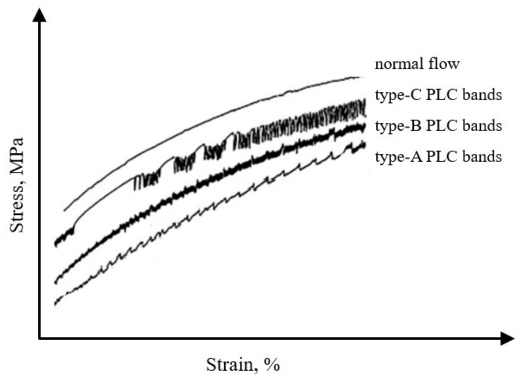

Figure 1. Three main types of deformation lines of the PLC effect

The occurrence of the PLC effect poses a challenge from both optical and structural perspectives. Aluminum alloy products where the PLC effect occurs during deformation can develop rough and undesirable surface marks. These surface irregularities can act as initial cracks and stress concentrators, Initial cracks and stress concentrators may lead to fatigue-induced material failure during subsequent processing stages [10, 11]. Furthermore, while the PLC effect leads to increased stress, hardness, tensile strength, and strain hardening rate, it also reduces ductility, toughness, and sensitivity to strain rates [11]. Since the PLC effect can be observed in a variety of aluminum alloys, AlMg alloys are often chosen as the material for studying these phenomena [12]. Tensile testing is the most common method to investigate the presence of the PLC effect in these alloys [13]. On the microscopic scale, the widely accepted explanation for the PLC effect is based on the Cottrell model, also known as dynamic strain aging (DSA) [14, 15]. When a sufficient number of solute atoms accumulate around dislocations, their movement is constrained. This restriction leads to less mobile dislocations and a corresponding increase in stress. Once the stress level becomes high enough to allow the release or multiplication of these immobilized dislocations, a sudden drop in stress occurs. Recurring stress fluctuations interrupt the strain hardening curve, appearing as serrations on the stress-strain diagram [14, 15, 16].

Among the most important factors influencing the occurrence of the PLC effect are the composition of the alloy and the concentration of solute elements [17, 18]. Precipitates play a notable role in enhancing deformation localization and promoting the PLC effect during plastic deformation. Dislocation density and grain size are also important factors contributing to the manifestation of the PLC phenomenon [8], although their influence is not always pronounced. Researchers have investigated the effect of both temperature and strain rate on AlMg alloys with different magnesium contents [9, 19]. Their results showed that these two parameters substantially influence the occurrence of DSA.

As for strain rate, the PLC effect shows considerable sensitivity due to the interplay between moving dislocations and diffusing solute atoms. In AlMg alloys, this relationship is often characterized by a negative strain rate sensitivity (nSRS), where an increase in strain rate leads to a stress drop — an unusual behavior for metallic materials [9, 19]. It is noteworthy that lower strain rates tend to lead to higher amplitude serrations, while higher strain rates lead to more damped stress fluctuations. This behavior can be attributed to the fact that the solute atoms have more time to interact with the dislocations at lower strain rates, which enhances the serrated flow. Conversely, the limited diffusion of solutes at higher rates weakens or even eliminates the PLC effect.

The manifestation of the PLC effect arises from a complex interplay of variables, underscoring the need for continued research to elucidate the underlying mechanisms and to identify processing conditions under which this phenomenon can be minimized or avoided. During static tensile testing of metals, the mechanical energy that leads to plastic deformation is converted into heat. This causes an increase in the material temperature and is often observed in various studies using infrared cameras [20, 21]. The Portevin–Le Chatelier (PLC) effect is a major contributor to this phenomenon. The PLC effect is associated with localized plastic deformation, where strain is concentrated in narrow deformation bands. As the dislocations are temporarily held in place by solute atoms (e.g. Mg in AlMg alloys), the stress builds up until the dislocations break free and cause a sudden surge of movement. This abrupt release of energy is converted into heat, which generates a local temperature change in the samples. The cyclic pinning and unpinning of dislocations in the PLC regime can therefore lead to temperature peaks, even in a nominally isothermal test. By using infrared thermography to measure these local temperature increases during PLC events, a clear correlation between stress serrations and temperature rise was confirmed [22, 23].

The occurrence of the PLC effect is a complex phenomenon influenced by numerous factors, necessitating further research to deepen our understanding of its underlying mechanisms. The primary objective of this study was to examine the effect of testing rate on the PLC behavior in an AlMg alloy, as well as its impact on temperature variations during the initiation and propagation of the PLC bands.

2. MATERIAL AND RESEARCH

For the experiment, samples were taken from cold-rolled sheets of the Al-Mg alloy EN AW-5754. By CNC machining, dog bone specimens were produced for the tensile test with the dimensions of the test part of 50 x 20 mm and 3 mm thickness.

To enable temperature and deformation measurements, the specimens were properly prepared by first applying a black matte spray coating, followed by a white speckle pattern necessary for DIC analysis (Figure 2).

Figure 2. Dog-bone specimen prepared for simultaneous tensile strength – DIC - thermography testing

The DIC analysis was performed with the ARAMIS system, Figure 3, and the thermography with the Jenoptik VarioCAM® IR camera, Figure 4. In the DIC analysis of the recorded changes during the appearance and propagation of the PLC lines, the change in the strain rate of the lines themselves was recorded. At the same time, the temperature changes caused by the deformation during the propagation of the PLC lines were monitored with the infrared camera.

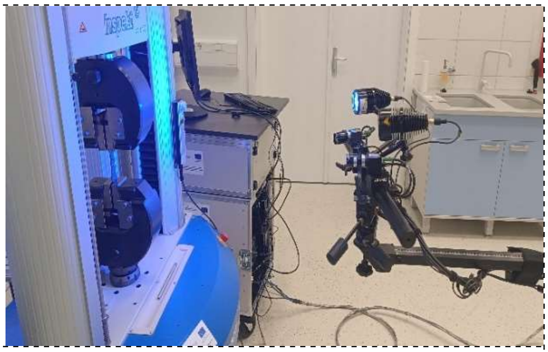

Figure 3. Experimental setup of ARAMIS system and Hegewald & Peschke inspect table 100 tensile testing machine

Figure 4. IR camera Jenoptik VarioCAM®

The tensile test was performed using a universal testing machine (Figure 3). During the tensile test, the deformation and the temperature change were recorded simultaneously. To determine the influence of the test speed on the temperature changes during the formation and propagation of the PLC, the tests were carried out at speeds of 10 mm/min, 20 mm/min, and 50 mm/min.

3. RESULTS AND DISCUSSION

Figure 5 shows the stress-strain curves obtained from static tensile tests at all three test speeds used. The plotted graphs, including the enlarged segment in Figure 5, clearly illustrate the jagged deformation characteristic of the material caused by the PLC phenomenon. These results indicate that the fundamental nature of the PLC effect remains unchanged as the test rate increases. During the static tensile test, the surface of the samples was continuously recorded with an optical camera and an infrared camera, and all images were subsequently analyzed. Figure 6 shows the DIC analysis of the strain rate and IR temperature changes of the PLC lines during the tensile test at a speed of 50 mm/min.

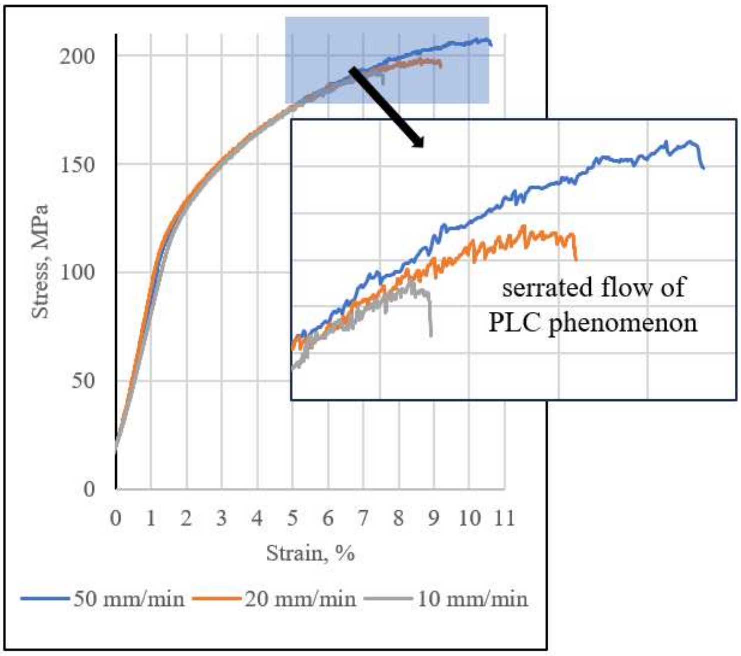

Figure 5. Tensile test results with visible occurrence of the PLC effect

Figure 6a shows a DIC analysis of the PLC lines during the tensile test, which reveals the propagation of a PLC line throughout the sample. Towards the end of the observed period, a second line appears from above, intersecting the first and forming an X-shaped pattern. From this, you can see that the phenomenon itself is very random and unpredictable. Figure 6b shows the same sample taken with an infrared camera. It shows the same phenomenon and correlates with the DIC recording. This confirms that the observed temperature change is directly caused by the deformation caused by the progression of the PLC line.

Figures 7, 8, and 9 show the results of the DIC and thermographic analysis of the recorded deformations at test speeds of 10, 20, and 50 mm/min respectively.

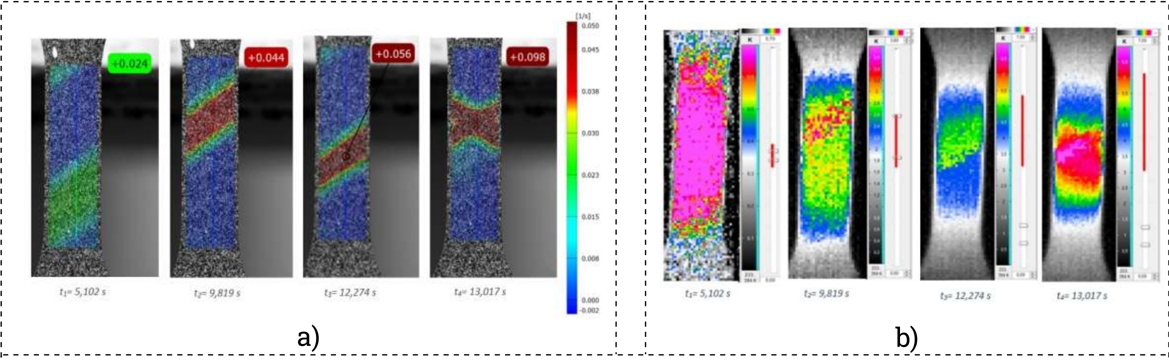

Figure 6. a) DIC representation of the propagation of the PLC line at a speed of 50 mm/min, b) Temperature changes due to the deformation of the PLC line at the same test points as DIC.

The images show comparisons of the strain rate changes and the associated temperature changes. The first thing that can be seen is that as the degree of deformation increases during the experiment, the strain rate and temperature change gradually increase. It can also be observed, as is to be expected, that as the test speed increases, the strain rate and the associated temperature rise increase more sharply.

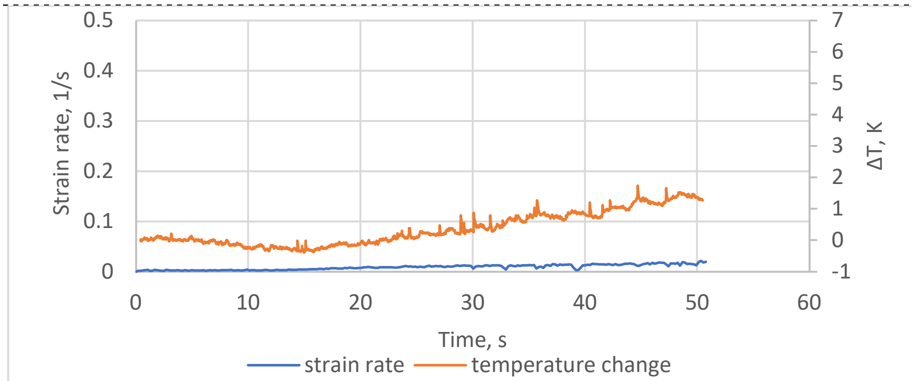

Figure 7. Comparison of change in strain rate and temperature at 10 mm/min

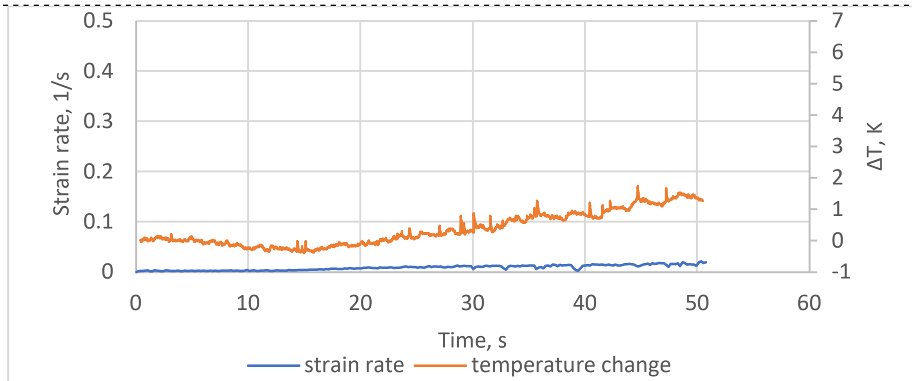

Figure 8. Comparison of change in strain rate and temperature at 20 mm/min

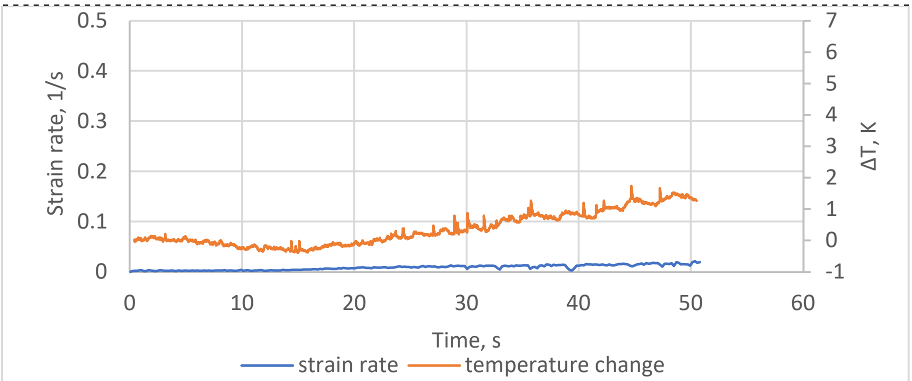

Figure 9. Comparison of change in strain rate and temperature at 50 mm/min

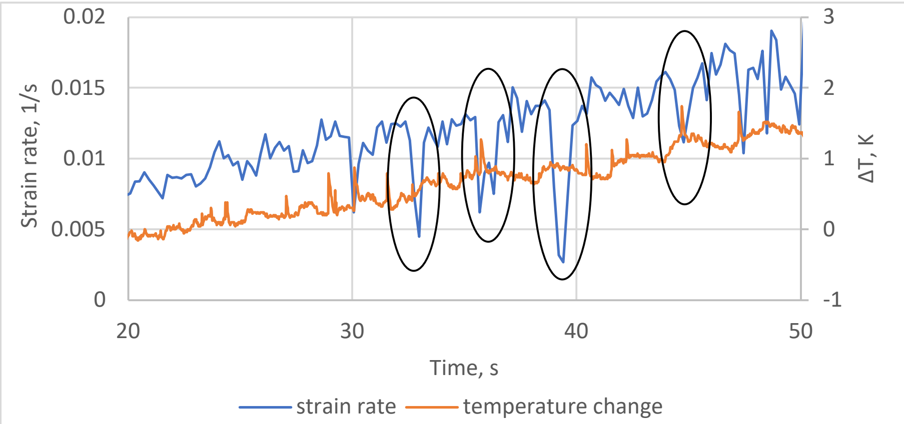

Figure 10. Segment of the comparison between the increase of strain rate and temperature at a test speed of 10 mm/min

What can be observed at all test speeds performed is the close relationship between the temperature change and the strain rate changes caused by the propagation of the PLC lines. This can be seen even more clearly from the enlarged section in Figure 10.

If you observe the changes in the strain rate closely, you can see that the strain rate of the PLC line drops suddenly at certain intervals. At the same time, it can be observed that a peak in the temperature change occurs at these moments. This can be seen at several points in Figure 10.

It is known that the increase in the temperature change is due to the work performed by the mechanical deformation, or more precisely by the plastic deformation of the sample. We can therefore assume that at the moments when we observe an increase in temperature, there is a greater plastic deformation at a constant strain rate. Consequently, we observe a decrease in the change in strain rate. To confirm this unequivocally, further investigations at other test speeds are required and a comparison must be made with the deformation amounts carried out during these periods.

4. CONCLUSION

The study confirmed a strong correlation between the propagation of the PLC bands, the variations in strain rate, and the temperature changes during the tensile test. Regardless of the test speed, the characteristic jagged curve associated with the PLC effect was consistently observed. As the deformation progressed, both the strain rate and the temperature increased, with the variations being more pronounced at higher test speeds.

Analysis of the recorded data revealed that temperature peaks coincided with abrupt drops in strain rate, indicating that localized plastic deformation was the primary cause of the observed thermal variations. Strain rate and temperature changes followed a clear trend, emphasizing the relationship between mechanical deformation and heat generation. These results suggest that the PLC effect remains essentially unchanged at different strain rates but varies in magnitude.

The formation of overlapping PLC lines showed the unpredictability of the PLC phenomenon. Further research is required to quantify the relationship between plastic deformation and temperature changes more accurately, particularly by testing at additional test speeds and comparing distribution patterns of temperature and deformation.

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Conflicts of Interest

The authors declare no conflict of interest.

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