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

Ivan Jandrlić[1], Lorena Mrkobrada[1]

[1] Faculty of Metallurgy, University of Zagreb, Aleja narodnih heroja 3
Corresponding author: Ivan Jandrlić, ijandrli@simet.hr

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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.

1. INTRODUCTION

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 leads to the formation of localized deformation lines that result in repetitive serrations in the stress-strain curve during tensile tests [6, 7]. Depending on the nature of serrations, three main types of deformation lines 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 lines such as types D and E have also been reported in the literature [8, 9].

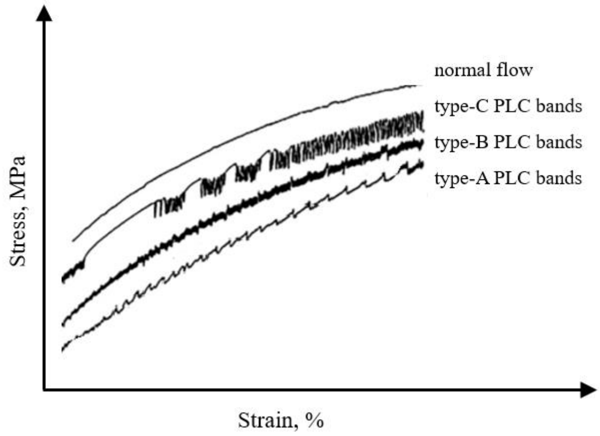

Figure 1. Three main types of deformation lines of the PLC effect

The occurrence of the PLC effect poses a challenge, both from an optical and structural point of view. Aluminum alloy products where the PLC effect occurs during deformation can develop rough and undesirable marks on their surface. These surface irregularities can act as initial cracks and stress concentrators, which can lead to material failure due to fatigue in further 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. The recurring stress fluctuations lead to interruptions in the strain hardening curve, which appear 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 that contribute to the manifestation of the effect [8], although their influence is not always significant. Researchers have investigated the effect of both temperature and strain rate on AlMg alloys with different magnesium contents [9, 19]. Their results show that these two parameters strongly 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 a 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 is determined by a complex interplay of variables, highlighting the need for ongoing research to better understand the mechanisms and identify processing conditions under which the effect can be minimized or avoided.
During static tensile testing of metals, the mechanical energy that leads to plastic deformation is converted into heat. This leads to an increase in the temperature of the material 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].

It is clear that the occurrence of the PLC effect is very complex and depends on numerous influencing factors, which imposes the need for further research on this phenomenon to better understand the phenomenon itself. The main objective of this search was to investigate the influence of the testing rate on the PLC effect in an AlMg alloy and its influence on the temperature changes during PLC formation and propagation.

2. MATERIAL AND RESEARCH METHODS

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.
For the measurement of temperature and deformation changes, the specimens were properly prepared by coating them with black mate spray and then applying the white speckle pattern required for DIC analysis, Fig. 2.

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

The DIC analysis was performed with the ARAMIS system, Fig. 3, and the thermography with the Jenoptik VarioCAM® IR camera, Fig. 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.

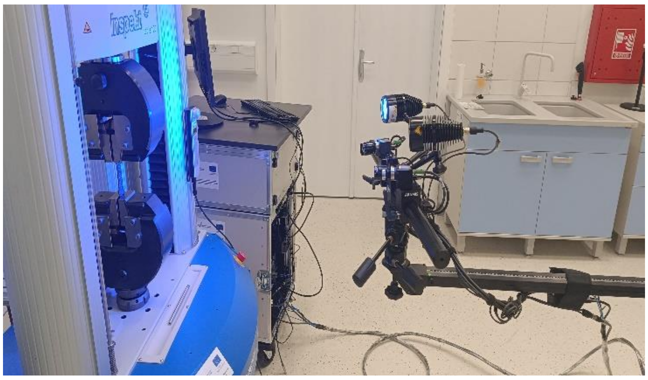

Figure 3. Experimental setup of ARAMIS system and tensile testing machine

Figure 4. IR camera Jenoptik VarioCAM®

The tensile test was carried out on the Hegewald & Peschke inspect table 100 tensile testing machine, Fig. 2. During the tensile test, the deformation and the temperature change were recorded simultaneously. In order 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 a speed 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.

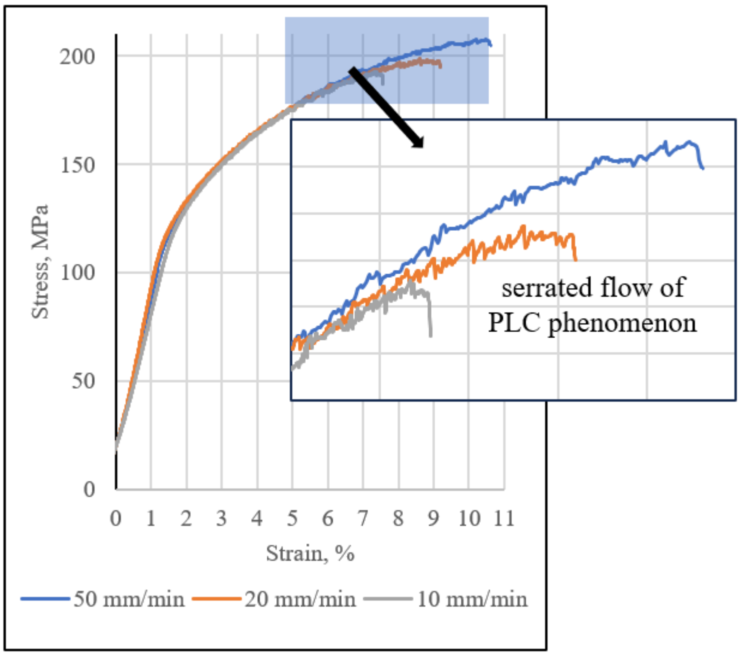

Figure 5. Tensile test results with visible occurrence of the PLC effect

The plotted graphs clearly show the jagged shape of the material due to the PLC phenomenon, Figure 5 enlarged segment. These results show that the nature of the PLC effect does not change as the test rate is increased. 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.

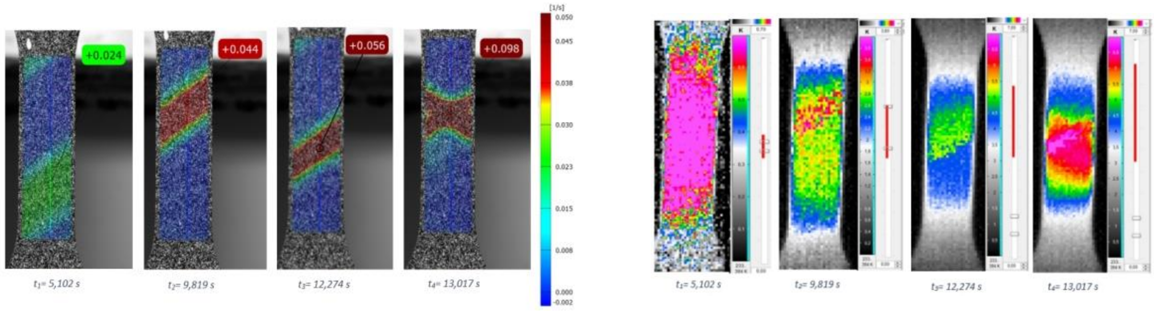

Figure 6. a) DIC representation of the propagation of the PLC line at a speed of 50 mm/min b) Temperature changes due to the deformation of the PLC line at the same test points as DIC

Figure 6 a 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.

Figure 7, Figure 8 and Figure 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.

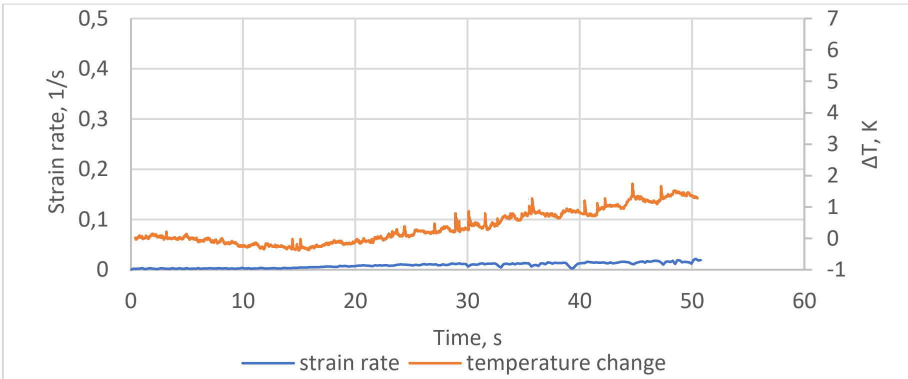

Figure 7. Comparison of change in strain rate and temperature at 10 mm/min

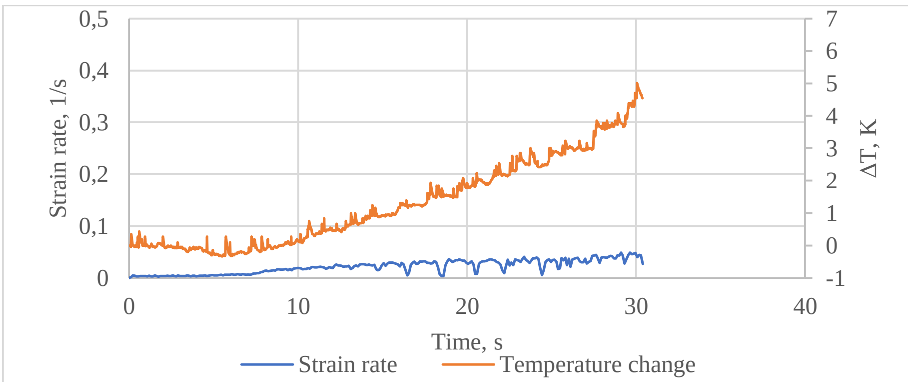

Figure 8. Comparison of change in strain rate and temperature at 20 mm/min

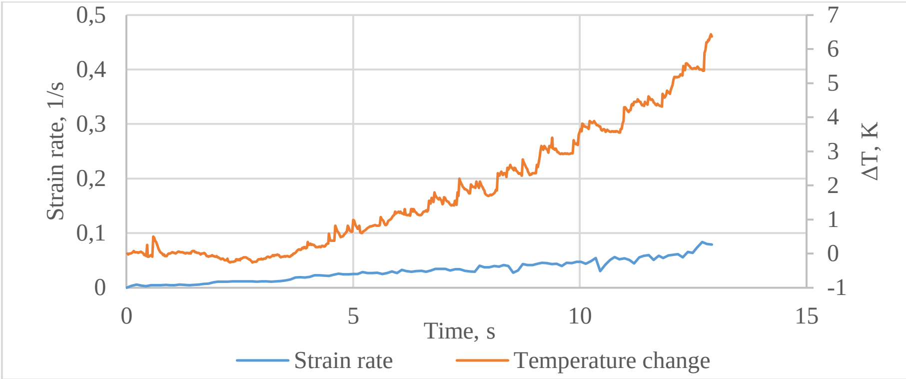

Figure 9. Comparison of change in strain rate and temperature at 50 mm/min

The images show comparisons of the strain rate changes and the associated temperature changes. The first thing that can be clearly 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.

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.

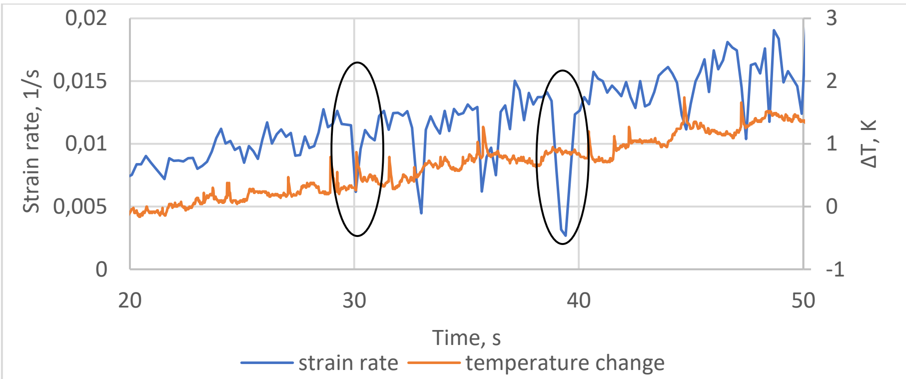

Figure 10. Segment of the comparison between increase of strain rate and temperature at a test speed of 10 mm/min

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. Therefore, 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 lines, 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 showed that temperature peaks coincided with a sudden drop in strain rate, suggesting that localized plastic deformation was responsible for the observed thermal changes. 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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6. REFERENCES

[1] Skejić D, Boko I, Torić N. Aluminij kao materijal za suvremene konstrukcije. Gradjevinar. 2015 67 (11): 1075-1085. https://doi.org/10.14256/JCE.1395.2015
[2] Romhanji E, Popović M, Glišić D, Stefanović M, Milovanović M. On the Al-Mg alloy sheets for automotive application: Problems and solutions. Metalurgija 2024; 10: 205-216.
[3] Chiaberge M. New Trends and Developments in Automotive System Engineering. Intech Open. 2011; doi: 10.5772/552.
[4] Smallman R E, Ngan A H. Work hardening and annealing. Modern Physical Metallurgy, 2014; 443-471, doi: 10.1016/B978-0-08-098204-5.00011-0.
[5] Farber V M, Morozova A N, Khotinov V A, Vichuzhanin D I, Karabanalov M S, Veretennikova I A. Lüders deformation in specimens made of normalized 09G2S steel. Procedia Structural Integrity, 2021; 40: 129-135. doi: 10.1016/j.prostr.2022.04.017.
[6] Zhemchuzhnikova D, Lebyodkin M, Yuzbekova D, Lebedkina T, Mogucheva A, Kaibyshev R. Interrelation between the Portevin Le-Chatelier effect and necking in AlMg alloys. International Journal of Plasticity. 2018; 110: 95-109. doi: 10.1016/j.ijplas.2018.06.012.
[7] Szalai S, Harangozó D, Czinege I. Characterisation of inhomogeneous plastic deformation of AlMg sheet metals during tensile tests. IOP Conference Series: Materials Science and Engineering, 2020; 903 (1). doi: 10.1088/1757-899X/903/1/012023.
[8] Zhemchuzhnikova D A. Influence of the extreme grain size reduction on plastic deformation instability in an AlMg and AlMgScZr alloys. Materials, Université de Lorraine, 2018. Available online: http://www.culture.gouv.fr/culture/infos-pratiques/droits/protection.htm
[9] Xu J, Holmedal B, Hopperstad O S, Mánik T, Marthinsen K.Dynamic strain ageing in an AlMg alloy at different strain rates and temperatures: Experiments and constitutive modelling. International journal of plasticity. 2022;151 (4): 103215. doi: 10.1016/j.ijplas.2022.103215.M.A.

[10] Lebyodkin M.A., Lebedkina T. A. The Portevin-Le Chatelier Effect and Beyond, Jamieson Brechtl; Peter K. Liaw. High-Entropy Materials: Theory, Experiments, and Applications, Springer Nature Switzerland, 2021. online https://hal.univ-lorraine.fr/hal-03360977v1/file/The%20Portevin-Le%20Chatelier%20Effect%20and%20Beyond_MLTL.pdf
[11] Tretyakova T. V, Tretyakov M. P, Chechulina E. A. Experimental study of the Portevin-Le Chatelier effect under complex loading of Al-Mg alloy: procedure issues. Frattura Ed Integrita Strutturale-Fracture and Structural Integrity, Oct 2021; 58: 434-441. doi: 10.3221/igf-esis.58.31.
[12] Borisova Y, Yuzbekova D, Mogucheva A. Influence of phase composition on Portevin-Le Chatelier effect in Al-Mg alloys. IOP Conference Series: Materials Science and Engineering, 2019/8// 2019; 597: doi: 10.1088/1757-899X/597/1/012057.
[13] Szalai S, Harangozó D, Czinege I. Characterisation of Inhomogeneous Plastic Deformation of AlMg Sheet Metals during Tensile Tests. IOP Conference Series: Materials Science and Engineering, 2020/8// 2020; 903: doi: 10.1088/1757-899X/903/1/012023.
[14] Yuzbekova D, Mogucheva A, Borisova Y, Kaibyshev R. On the mechanisms of nucleation and subsequent development of the PLC bands in an AlMg alloy. Journal of Alloys and Compounds, 2021; 868: doi: 10.1016/j.jallcom.2021.159135.
[15] Cottrell, A.H., "Theory of dislocations," Progress in Metal Physics, 1953; 4: 205-264. doi: https://doi.org/10.1016/0502-8205(53)90018-5.
[16] Mehenni M, Ait-Amokhtar H, Fressengeas C. Spatiotemporal correlations in the Portevin-Le Chatelier band dynamics during the type B - type C transition. Materials Science and Engineering A, 2019; 756 (5): 313-318, doi:10.1016/j.msea.2019.04.036.
[17] Mäkinen T, Karppinen P, Ovaska M, Laurson L, Alava M. J. Propagating bands of plastic deformation in a metal alloy as critical avalanche. Science Advances. Oct 2020; 6(41): doi: 10.1126/sciadv.abc7350
[18] Kang J, Shi L, Liang J, Shalchi-Amirkhiz B, Scott C. The Influence of Specimen Geometry and Strain Rate on the Portevin-Le Chatelier Effect and Fracture in an Austenitic FeMnC TWIP Steel. Metals. 2020; 10 (9): 1201-1201, 2020, doi: 10.3390/met10091201.
[19] Cho C. H., Son H. W., Lee J. C., Son K. T., Lee J. W., Hyun S. K. Effects of high Mg content and processing parameters on Portevin-Le Chatelier and negative strain rate sensitivity effects in Al–Mg alloys. Materials Science and Engineering A, 2016; 779 (3): 139151 doi: 10.1016/j.msea.2020.139151.
[20] Jandrlić I, Rešković, S, Brlić, T. Distribution of stress in deformation zone of niobium microalloyed steel. Metals and materials international. 2018; 24 (4): 746-751. doi: 10.1007/s12540-018-0099-2
[21] Wang X.G., Crupi V., Guo X.L., Zhao Y.G. Quantitative thermographic methodology for fatigue assessment and stress measurement. International journal of fatigue. 2010; 32 (12): 1970-1976 https://doi.org/10.1016/j.ijfatigue.2010.07.004
[22] Le Cam JB, Robin E, Leotoing L, Guines D. Calorimetric analysis of Portevin-Le Chatelier bands under equibiaxial loading conditions in Al–Mg alloys: Kinematics and mechanical dissipation. Mechanics of Materials, 2017; 105: 80-88. doi: https://doi.org/10.1016/j.mechmat.2016.11.012
[23] Qi Hu, Zhang Q, Cao P, Fu S. Thermal analyses and simulations of the type A and type B Portevin–Le Chatelier effects in an Al–Mg alloy. Acta Materialia, 2012; Feb 60 (4):1647-1657. doi: https://doi.org/10.1016/j.actamat.2011.12.003