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Investigation of the Portevin-Le Chatelier effect by the acoustic emission

B. Grzegorczyk*, W. Ozgowicz, E. Kalinowska-Ozgowicz, A. Kowalski
Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding e-mail address: barbara.grzegorczyk@polsl.pl

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Materials

ABSTRACT

Purpose: The aim of this paper is to determine the relation existing between the behaviour of the signals of acoustic emissions generated in the course of plastic deformation at elevated temperature, and the shape of the work-hardening curves σ-ε and the Portevin - Le Chatelier effect.

Design/methodology/approach: Single crystal was investigated applying the method of free compression at a constant strain rate and a temperature within the range from 20°C to 400°C at a strain rate of 10^{-5} sec^{-1} to 10^{-1} sec^{-1}, simultaneously recording this phenomenon by means of acoustic emission.

Findings: The analysis of the results of these investigations permitted to prove considerable relations between the work-hardening curve σ-ε displaying the PLC effect and the characteristics of the signals of the acoustic emission generated in the uniaxial compression.

Practical implications: The AE method applied in the process of plastic deformation of single crystals of the alloy CuZn30 displays also a dependence of the activity of acoustic emissions on the stage of strain-hardening of the investigated alloy.

Originality/value: In the range of the occurrence of the PLC effect during the compression test of the investigated single crystals the signal AE displays a cyclic character, distinctly correlated qualitatively with the oscillations of stresses on the curve σ-ε.

Keywords: Copper alloys; Single crystals; Acoustic emission (EA); Portevin-Le Chatelier (PLC) effect

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1. Introduction

Plastic deformation is a fundamental process of change of geometric features of solids under the influence of internal or external forces, on which technology of plastic working is based. Therefore, knowledge of mechanisms of plastic deformation has an essential cognitive and application significance. The development of crystallography and research methods and most of all techniques which use X-ray, electron and neutron diffraction, contributed significantly to the development of materials science, and in particular - to the knowledge of plastic deformation of metals and commercial alloys. Knowledge of the course and understanding the essence of various phenomena occurring during the process of plastic deformation is indispensable to determine kinetic dependences and structural changes which condition the mechanisms of deformation and allows proper programming of technological cycle of hot and cold working in the industrial practice. Each plastic deformation is a complex process, consisting in diverse and often very specific interaction and organization of elementary acts of slip or twinning.

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Phenomenon of heterogeneous plastic deformation, manifesting itself as irregularities on the σ-ε hardening curve, called Portevin - Le Chatelier (PLC) effect, occurs in many metal alloys during deformation in a defined temperature range and strain rate (Fig. 1) [1-6].

The profile of research of this phenomenon (effect) proposed by Portevin and Le Chatelier focused their attention on instability of force during tension. Modeling such behaviour and explanation of physical causes of instability seemed to have essential significance for understanding this phenomenon. Since deformation physics did not have either qualitative or quantitative tools for the description of elementary deformational processes, the analysis of the causes of instability in terms of physical models has had to be qualitative. The explanations of the phenomena given by Jasiewicz in 1930 had such nature.

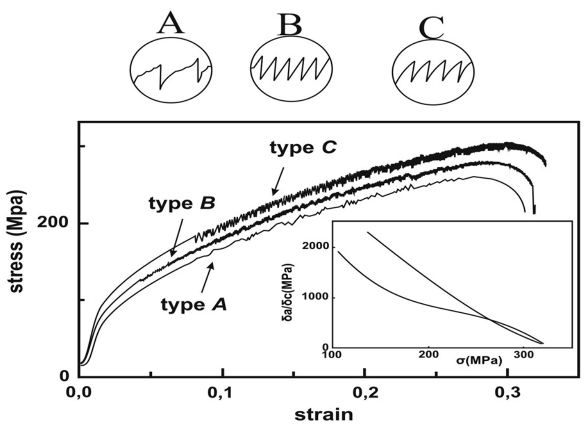


Fig. 1. Types of stress oscillation occurring on the stress-strain curve [3]

It was not until the advances of the dislocation theory and Orowan's works allowed to present quantitative relationship between deformation and path of movement and density and dislocation velocity in micro-areas of crystals, which could provide the basis for creation of physical models of deformational phenomena.

There are several models of the PLC effect fundamentally presented in the literature [2-11], that is:

- the Cottrell model, based on physical foundations of interaction of foreign atoms and dislocation,
- the model of dynamic pile-up of dislocations (given by A. Korbel),
- the Jasieński model - cross-slip of active dislocations at specified stress levels,
- the Kubin (et. al.) model of precipitations shearing by active dislocations,
- the dislocation dynamics model (elaborated by A. Pawełek).

The Cottrell theory [2] is most common and conditions the presence of the PLC effect with the changes of movement velocity of dislocations limited with migrations of foreign atoms forming impurity clusters around dislocations. The effect is connected with detachment of dislocations from anchoring impurity atmospheres of foreign atoms formed in the process of dynamic ageing. Other theories explain this effect with interaction of dislocations with point defects, pipe diffusion through dislocation forest or via dynamic model of flat pile-up of groups of dislocations and propagation of located plastic deformation areas via grain boundaries.

The Portevin - Le Chatelier effect is generally considered on the basis of material factors - taking into consideration microstructural conditions of initiation of development of localized plastic deformation and rheological factors - related to the mechanisms of plastic deformation in various thermodynamic and physicochemical conditions. Processes responsible for the appearance of the PLC effect are not yet fully explained and views concerning physical bases of the phenomenon are diversified.

For the purpose of investigating the PLC effect of the instability of deformation usually conventional mechanical tests of uniaxial tension or compression are applied, but also modern methods are used, e.g. the digital correlation of the image or acoustic emission (AE) [12-15]. Investigations making use of acoustic emission consist in the detection and analysis of acoustic signals emitted by the material in the course of its being mechanically loaded. The acoustic signal results from the propagation of elastic waves generated in the material due to the rapid release of the energy accumulated in this material. The release of elastic strain energy in some materials is connected with the formation of instantaneous local unstable states, which may result from processes accompanying miscellaneous phenomena, viz. from those occurring in the submicroscopic scale, e.g. diffusion of atoms into adjoining positions of the crystalline lattice, to phenomena in the macroscopic scale, e.g. cracking of the material. The plastic deformation of metals and alloys is directly connected with the dis1ocation movement depending on the microstructure of the material. Acoustic emission is applied in investigations concerning the PLC effect as a highly sensitive method of measuring elastic waves arising in the material due to the dynamic local reconstruction of the structure. Comparing the obtained AE results with the diagrams of tensile tests, we can analyze the effect of various parameters of deformation on the PLC phenomenon. This method is often used in investigations of precipitation of hardened alloys, because in them frequently two mechanisms turn up, conditioning the PLC effect, viz. the effect of foreign atoms with dislocations (Cottrell's model) and the shearing of precipitations. Investigations involving AE measurements are characterized by non-invasive propensity and an incomparably high sensitivity in recording the physical phenomena in comparison with other methods of investigations [16,17].

The aim of this paper is to determine the relation existing between the behaviour of the signals of acoustic emissions generated in the course of plastic deformation at elevated temperature, and the shape of the work-hardening curves σ-ε and the PLC effect.

2. Experimental procedure

The material investigated was the single crystalline CuZn30 alloy in the form of a rod with the diameter 3.8 mm, a length of about 200 mm and the crystallographic orientation [$\bar{1}$ 3 9], the chemical composition of which is to be seen in Table 1. Single crystals of this alloy were obtained making use of Bridgmen's method in a vertical laboratory electrical tubular heating furnace by displacing the temperature gradient of the zone in the furnace in relation to the crucible (a quartz tube) with a charge in the atmosphere of inert gas.

In order to determine the temperature effect of compression on the mechanism of the Portevin-Le Chatelier phenomenon in single crystalline CuZn30 the following tasks had to be undertaken:

- mechanical free compression tests of single crystals with a crystallographic orientation [$\bar{1}$ 3 9] at elevated temperature,
- investigations concerning the process of plastic deformation of single crystals by means of acoustic emission.

Compression tests of single crystals were performed within the temperature range of 200°C to 400°C at strain rate ($\dot{\varepsilon}$) of $10^{-5}s^{-1}$-$10^{-1}s^{-1}$ using a testing machine INSTR0N 3382, equipped with a duct die, containing heating elements and an quartz outlet of the waveguide and AE sensors (Fig. 2). In the uniaxial free compression test the duct-die block (matrix) played merely the role of the holder of the sample exerting pressure of the external force, whereas its bottom plate is also applied as a natural metallic conductor for signals of acoustic emission generated in the tested single crystalline sample. In this way an original solution was attained concerning the problem of the contact between the tested sample and the sensor of acoustic emission. These investigations were carried out at the Accredited Laboratory of Strength of Materials, Polish Academy of Sciences, in Cracow. The final deformation of the sample after the compressive test was about 50% and the accuracy of the recorded force within the entire range of measurements up to 0.5%.

detail design

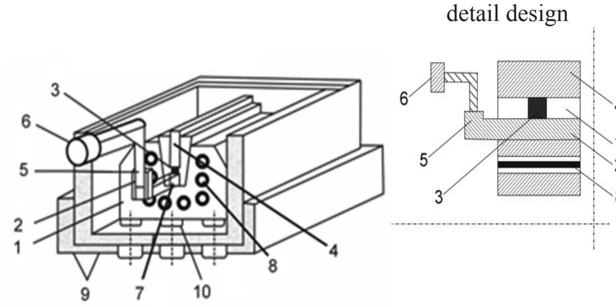


Fig. 2. Duct die block for the deformation of samples at elevated temperature by means of an AE probe: 1-body die block, 2-quide bar, 3-sample, 4-punch, 5-wave-guide, 6-AE probe, 7-duct, 8-heating elements, 9-foamed polystyrene, 10-tackbolt

The acoustic emission was measured during the tests of free compression of single crystalline samples in the form of a rod with the diameter of 3.8 mm and initial length of about 6 mm. For these investigations were selected single crystals, whose surfaces displayed the least porosity. In order to reduce the coefficient of friction between butting face of the compressed sample and the steel punch an interlayer of thin (75 μm) teflon (PTFE) foil was applied, the advantage of which is that it does not introduce an additional source of acoustic emission. The block diagram of the measuring and recording system AE has been presented in Fig. 3. The measuring system AE is connected with the system recording the results of the testing machine.

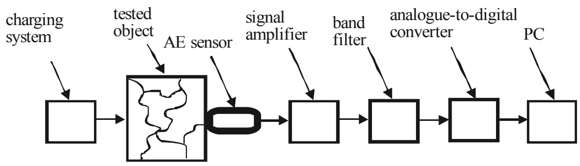


Fig. 3. Simplified block diagram measuring and recording system of the AE

3. Results and discussion

The diagram presented in Fig.4 illustrates the deformation temperature influence on the mechanical characteristics in compression tests of single crystals alloy type CuZn30 with an initial crystallographic orientation [$\bar{1}$ 3 9]. The influence of the strain rate in the range of $10^{-5}s^{-1}$-$10^{-1}s^{-1}$ on the mechanical characteristics σ-ε of CuZn30 single crystals at a constant temperature of compression amounting to 300°C has been presented in Fig. 5.

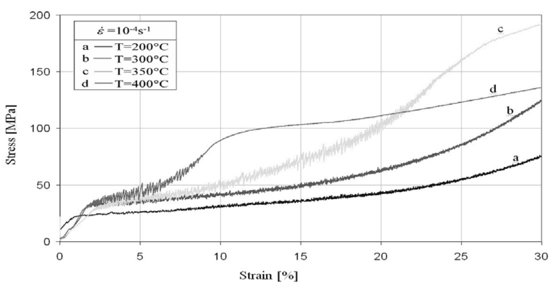


Fig. 4. The effect of the deformation temperature on the shape of the σ-ε curves of CuZn30 single crystals with an initial orientation [$\bar{1}$ 3 9], compressed in the range of temperature from 200°C to 400°C at a strain rate up to about $10^{-4}s^{-1}$

Table 1.
Chemical composition of the alloy for the production of single crystals

No.	Denotation of the alloy and the type of analysis	Chemical composition, % by weight						
		Zn	Fe	Al	Ni	Sn	Pb	Cu
1	CuZn30 ingot analysis of smelting	30.3	0.024	0.039	0.024	0.003	0.01	rest.
2	CuZn30 PN-EN 12163:2002	28.3-30.3	max 0.05	max 0.02	max 0.3	max 0.1	max 0.05	rest.

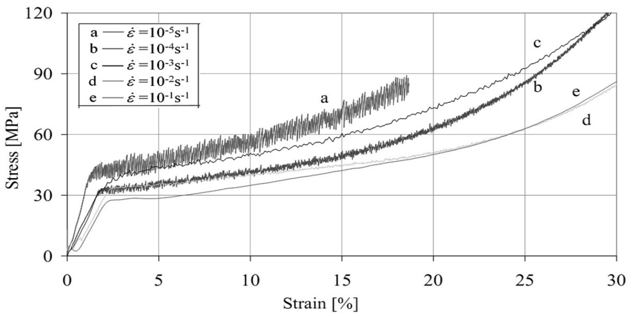


Fig. 5. The influence of the strain rate on the shape of the curves σ-ε of CuZn30 single crystals with the initial orientation [$\bar{1}$ 3 9] compressed at 300°C

Compression curves obtained in the range of temperature from 200°C to 400°C at a constant strain rate $\dot{\varepsilon}$, of about $10^{-4}s^{-1}$ display a differentiated character of strain hardening in its respective stages. Although all of them display distinct oscillations of the force, which indicates the occurrence of the PLC phenomenon. The PLC effect starts in the analyzed curves in the range of critical deformation (ε_c) up to about 1.5-2%. The starting of oscillations on the compression curves coincides mostly with the range of the yield point of the material. It has been found that the quantity ε_c does not depend actually on temperature of deformation, whereas values of amplitude of stress oscillation Δσ and the oscillation character depend on it. In the case of samples compressed at 200-350°C oscillations of the stress on the curves are observed in all stages of strain-hardening of single crystals. It has been found that the strain rate does not affect much the shape of the work-hardening curves of the single crystals and affects only slightly the range of the stages of hardening and values of the yield stress. The increase of the strain rate involves a reduction of true stresses, particularly in the case of small values of deformation (about 15%), respectively in the first and second stage of hardening.

At the temperature of compression 300°C, the strain rate influences considerably the intensity of oscillation of the stresses characterized by the occurrence of the PLC effect. Conditions of plastic instability of the deformed single crystals are distinct in the case of low values of $\dot{\varepsilon}$ ($10^{-5}s^{-1}$-$10^{-4}s^{-1}$) but fade at a medium strain rate of about $10^{-3}s^{-1}$ and do not occur when $\dot{\varepsilon} > 10^{-2}s^{-1}$-$10^{-1}s^{-1}$. It has also been found that the strain rate affect only slightly the type of oscillation of the stress in the described deformation conditions.

Selected results of measurements concerning the energy of acoustic emissions in the compression test of investigated single crystals have been gathered in the diagrams (Figs. 6, 8). In most cases of compression tests a distinct increase in AE energy activity was recorded during the initial stage of compression and in the transition zone from the elastic to the plastic range. The rising activity of the energy AE is in both cases characterized by a more or less wide maximum of the energy of the signal, after which the energy AE reaches its minimum. The observed increased AE energy activity in the initial stage of the curves σ-ε may, however, be caused, among others, by mechanical factors due to friction in the course of matching the sample to the pressure of the punch in the testing machine. In the range of the yield point, the increased AE energy activity is connected without any doubt with the dislocation processes.

Table 2 provides a comparison of the sum and average energy of occurrences depending on the temperature of deformation in the compression test. It has been found that the sum of events of AE in the range of the yield point (R_e) grows together with the temperature, similarly as the average energy of a single occurrence. The highest sum of the number of events was attained in the case of deformed single crystals with $\dot{\varepsilon}$ to about $10^{-4}s^{-1}$ at a temperature of 400°C and a mean value of energy (25 pJ), and the lowest in the case of samples compressed at 200°C, the mean value of the energy of event of about 12 pJ.

The sum and mean energy of AE depending on the strain rate during the compression test have been gathered in Table 3. It has been found that in the range $\dot{\varepsilon}$ from about $10^{-4}s^{-1}$ to about $10^{-2}s^{-1}$ the sum of events in the range of the occurrence of the yield point (R_e) increases with the slowing down of the strain rate. The opposite is the case when the energy of a single event reaches its mean value. To a smaller sum of events corresponds a higher average value of the energy of the event except $\dot{\varepsilon}$ amounting to about $10^{-1}s^{-1}$, the minimum sum of events of about 816 corresponds also to the low value (30pJ) of the average energy of the events AE . The highest sum of the number of events occurred in the case of single crystals deformed at a temperature of 300°C with $\dot{\varepsilon}$ amounting to about $10^{-4}s^{-1}$ and a mean value of the energy of event of about 20 pJ.

Table 2.
Results of the analysis AE signal of single crystals compressed at a strain rate of about $10^{-4}s^{-1}$ depending on the temperature of the test

No.	Temperature of deformation [°C]	Sum of occurrences of AE in the range of the yield point (R_e)	Average energy of a single occurrence AE [pJ]
1	200	9990	12
2	300	14539	20
3	350	16566	17
4	400	34253	25

Table 3.
Specification of the descriptor of the signal AE in the range R_e concerning the investigated parameters of compression

No.	Temperature of deformation [°C]	Strain rate, $\dot{\varepsilon}$ s^{-1}	Sum of AE events in the range R_e	Average energy of the AE events in the range R_e [pJ]
1	300°C	10^{-4}	14539	20
2		10^{-3}	8903	42
3		10^{-2}	6714	68
4		10^{-1}	816	30

In order to analyze in detail the behaviour of AE and to determine the correlation with the effect of the mechanical oscillation of stresses on the curves σ-ε in the course of compressing the investigated single crystals at elevated temperature, the obtained signals were subjected to successive digital processing, applying software concerning acoustic analyses, in this particular case concerning sounds which are audible for the human ear. In order to facilitate an acoustic interpretation of these sounds, their amplitude was amplified by about 500% and in some cases slowed down tenfold. Representative characteristics of AE have been presented in the diagram and acoustogram (Figs. 7, 9). The spectral characteristics of the recorded sonic signals were analyzed, as well as the time dependence in the range of 5% deformation of the sample after the appearance of the PLC effect on the curve. The intensity of the spectral density function is marked on the acoustogram by a blue code.

It has been found that in most cases of compression tests of single crystals displaying the PLC effect, the local rapid drops of the load recorded on the force-time curve are distinctly correlated with the AE peaks. According to Cottrell's theory this may be due to avalanche separation of the dislocations from the atmospheres of foreign atoms which have been blocking them. The most evident correlation of these effects was recorded in the case of samples compressed at 400°C (Fig. 7).

The latter one is a part of Fig. 6, in which the unit of time has been expanded. Practically, about 500 seconds of AE have been recorded during the compression test, with special regard to the correlation: load - AE. The compression test generates and propagates the highest sounds with an intensity of about 54 dB within the frequency range from 4320 Hz to 8640 Hz.

It has been found that in the first stage of hardening (the stage of easy sliding) of single crystals which do not display any PLC effect, the AE level is lower, growing with the increase of the rate of deformation, whereas in single crystals displaying the PLC effect the AE level is respectively higher, and its characteristics are more complex. A change of the strain rate at a given temperature does not involve any essential changes in the level of the frequency of AE. In the second stage of hardening within the range $\dot{\varepsilon}$ ($10^{-5}s^{-1}$-$10^{-1}s^{-1}$) the activity AE is greater, particularly during the initial stage. These are mostly single samples of the AE signal characterized by a differentiated energy or a continuously increasing level of AE energy, which grows with the increasing rate of deformation, independent of the occurrence of the PLC effect in the course of the compression of the single crystals. When the work-hardening curve is of a parabolic character (third stage of hardening), AE appears in the form of strong cumulated maximum values of energy changes of the signal in time, particularly at the beginning. Irrespective of the appearance of the PLC effect in the course of the compression test of single crystals, it has been found that in the final stage of deformation there also appears an range, in which the AE energy is intensified, although less intensive with respect to the number of pulses than in the R_e range. The observed correlations between the behaviour of AE and the exerted compressive force and the evolution of the microstructure may be accounted for satisfactorily on the qualitative level basing on dynamic processes of dislocation connected with the dislocation motion [12-15]. Acoustically most effective proved to be the processes of the formation of sliding lines in the range of the yield point. Probably every collective dislocation motion in the systems of sliding leads to a release of elastic energy, which generates the recorded signals.

The obtained results permit to maintain that in the tested single crystals the PLC effect is the result of the dynamic strain ageing (DSA), which is an interaction between the sliding dislocations and the free atoms, or according to the dynamic-dislocation model due to the PLC effect and the multiplication of dislocations in the course of the operation of Frank Read (FR) sources. The occurrence of DSA is conditioned by the rate of the migration of foreign atoms constituting the Cottrell atmosphere. The effect of the atoms of the alloy and interaction with dislocations is responsible for the retarding of the dislocations, and thus also for the hardening of the alloy. If, therefore, some given strain rate is "imposed", we must also apply such a stress which exceeds the resistance of the dislocation motion, including the resistance resulting from the effect of the atoms of the alloy with dislocations. In order to justify in a simple way the qualitative model of changes of the stress in the diagram of hardening we must assume that the brake away of the dislocation from the atom of the alloy reduces the stress which is indispensable for the further displacement of the dislocation by the value of this effect. The moment of the break-off of the dislocation from the atoms which are blocking it involves a sudden drop of the force exciting the deformation [18-20]. According to the dynamic-dislocation model of the PLC effect, every local drop of the loading force recorded on the σ-ε curves is connected with the unblocking of the sources of dislocation in some definitely localized area the sample.

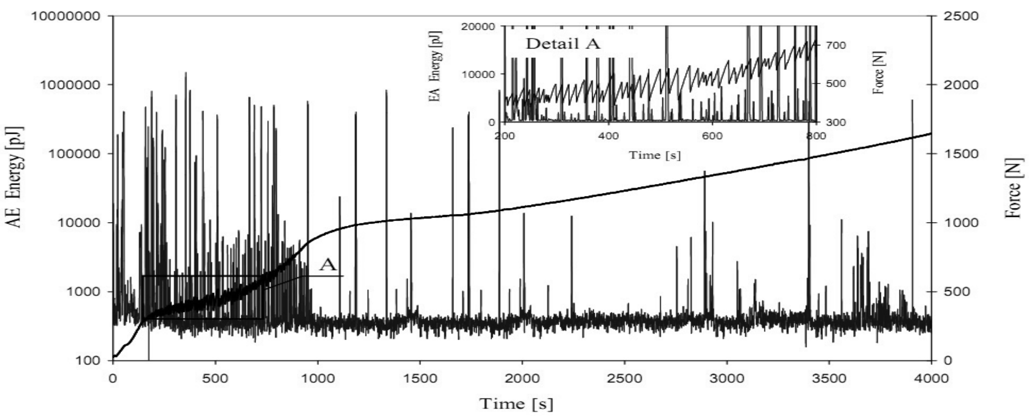
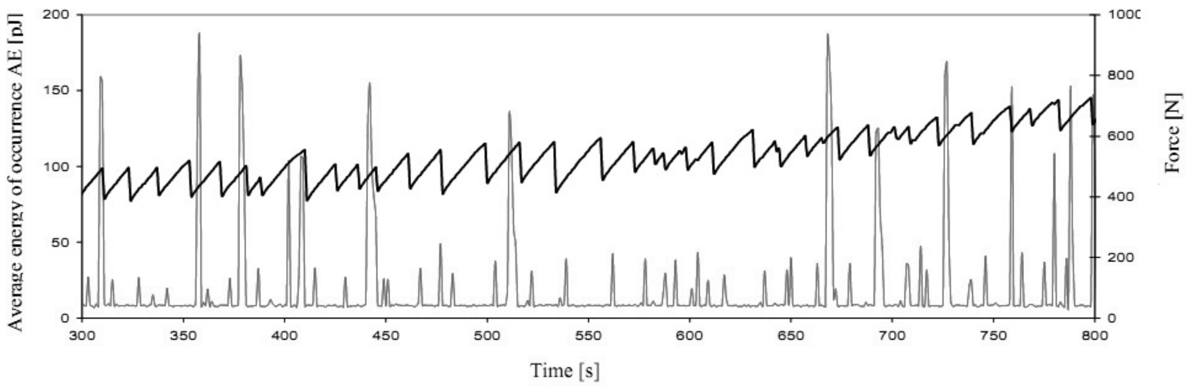


Fig. 6. The energy of acoustic emission and the external load during the compression test of the single crystalline alloy CuZn30 at 400°C with to about $10^{-4}s^{-1}$

a)



b)

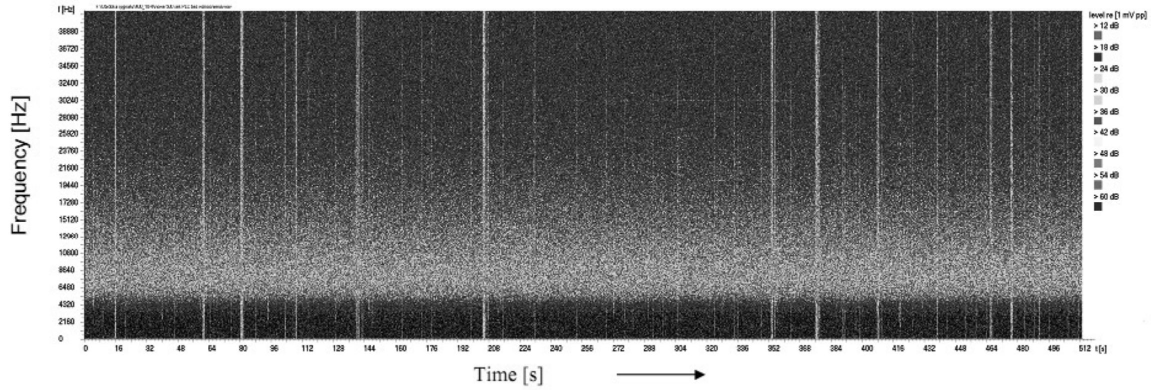


Fig. 7. Fragment of the diagram concerning the dependence of AE and the external force on the duration of the compression test (from 300 sec. to 800 sec.) of the monocrystal CuZn30 with the orientation $[\bar{1}\ 3\ 9]$ at the temperature of 400°C with $\dot{\varepsilon} = 10^{-4}s^{-1}$: a) average energy of occurrences AE; b) acoustogram of the set of occurrences AE presented in Fig. 7a

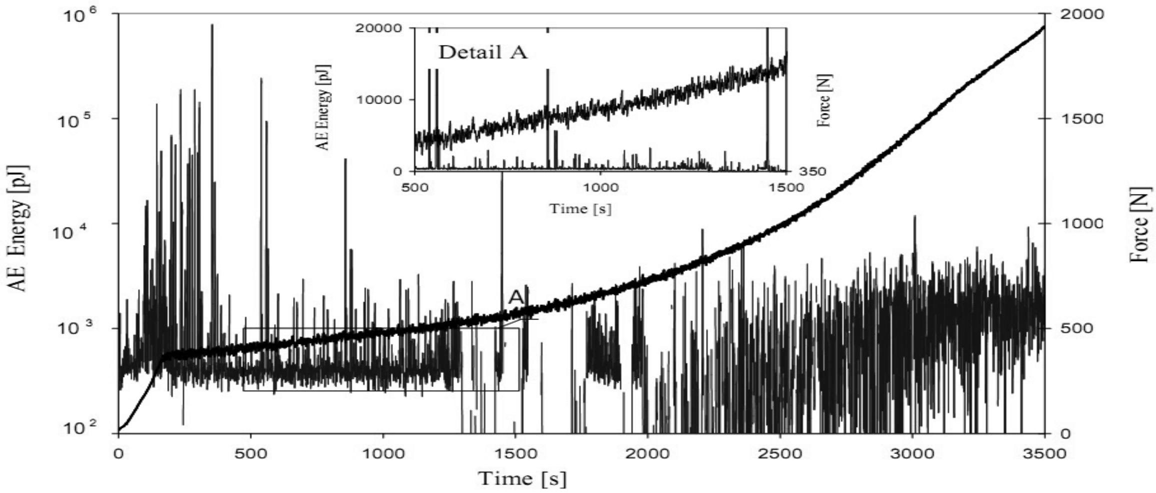
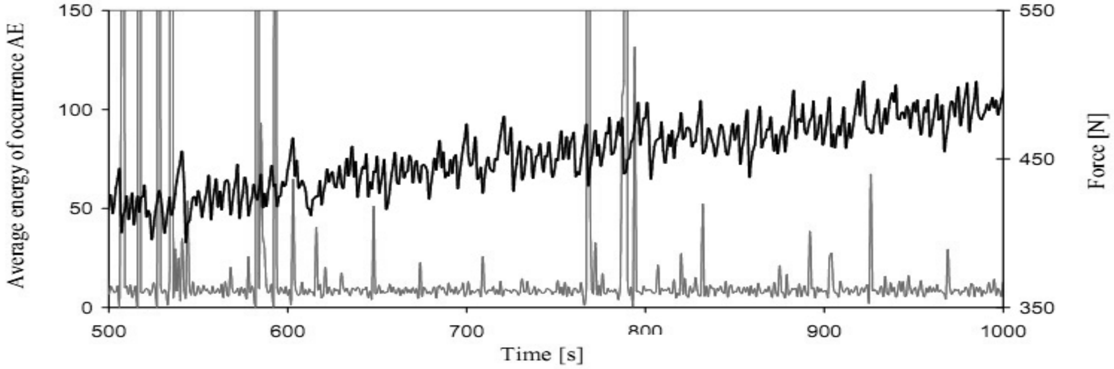


Fig. 8. Dependence of the acoustic emission and load on the duration of the compression test of a CuZn30 single crystal at 300°C and $\dot{\varepsilon}$ amounting to about $10^{-4}s^{-1}$

a)



b)

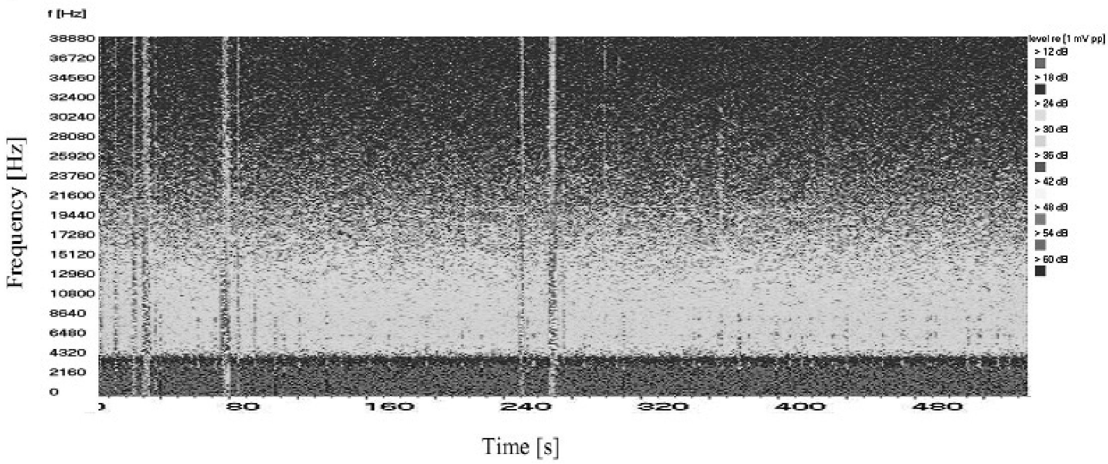


Fig. 9. The dependence of AE energy and load on the duration of the compression test (part of the diagram presented in Fig. 8) of the single crystal CuZn30 with the orientation $[\bar{1}39]$ at 300°C and $\dot{\varepsilon}$ amounting to about $10^{-4}s^{-1}$: a) mean energy of AE events, b) acoustogram of the set of AE events presented in Fig. 9a

4. Conclusions

Basing on the investigations the following conclusions may be derived:

1. Single crystals of the alloy CuZn30 subjected to special conditions of free compression tests at elevated temperatures display the phenomenon of unstable plastic deformation, the so-called PLC effect, with characteristic oscillations of stresses, in literature classified as type B.
2. The process of plastic deformation of the investigated single crystals at elevated temperature generates in the analyzed range of frequencies (up to 35 kHz) diversified source of AE energy, mainly an impulsing emission from single events, i.e. pulsating acoustic signals with a high energy in the frequency band from 4 kHz to 8 kHz.
3. The applied AE method displays in the process of plastic deformation of the tested single crystals a dependence of the activity of acoustic emissions on the given stage of hardening of the analyzed alloy.
4. The increasing strain rate effects essentially in the given range changes of the intensity of oscillations of stress, typical for the PLC effect whereas do not involve essential changes in the frequency of AE. An acceleration of the strain rate leads, however, to a distinct decrease of the level of AE activity of the deformed samples in the tested range of plastic strain.

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