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ANISOTROPY OF ACOUSTIC EMISSION AND PORTEVIN–LE CHÂTELIER PHENOMENA IN POLYCRYSTALLINE ALUMINIUM ALLOYS SUBJECTED TO TENSILE TESTS

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In the present work the acoustic emission (AE) method has been used in the plastic instability investigations related to the Portevin–Le Châtelier phenomenon (PL effect, non-homogeneous strain, jerky flow) occurring in polycrystalline aluminium alloys subjected to tensile tests at ambient temperature. There have been observed very essential correlations between AE and PL phenomena and a strong anisotropy of both these effects in samples cut at various angles with respect to the initial rolling direction has been found. The results of AE measurements were obtained using a new AE analyser and, for a few samples, they have been compared with those obtained applying an analyser of older generation, used till now. Moreover, the new software allowed additionally to carry out the analysis of single AE events, which, in turn, created better possibility to determine the relations between the non-homogeneous strain mechanisms of the PL type and the mechanisms of AE events generation. The results are discussed also in the context of the existing models of the PL effect and the theoretical concepts of AE sources.

Key words: acoustic emission (AE), non-homogeneous strain, Portevin–Le Châtelier phenomenon (PL effect), jerky flow, tensile test, aluminium alloys, dislocations.

1. Introduction

The acoustic emission (AE) method is still useful in the investigations of the more physical aspects of the strain localization phenomena, particularly with reference to the PL effect (e.g. [9, 10, 13, 14]) as well as to the shear bands or twins formed during channel-die compression of metals in low temperatures [11, 12]. In both of these last works the strong correlation between the drops of external load and the peaks of AE has been observed, similarly as it was signalised earlier in the papers [9]. There exist no commonly accepted models which could be used to describe the physical causes of both PL and AE effects.

Most of these models (e.g. [1, 4, 8]) are of phenomenological character and none of them explains clearly the physical mechanisms of the formation and propagation of the related deformation bands and which would be coherent with the models of the sources of AE. Moreover, to our knowledge, there are no any reports in available literature on the suggestion that both PL and AE phenomena can reveal some anisotropic properties.

There are two important, basic parameters characteristic for the PL effect. The first one is the waiting time, t_w, which is involved in the expression for strain rate, $\dot{\varepsilon}$, in the following way:

$$\dot{\varepsilon} = b\rho L/(t_w + t_f), \tag{1}$$

where ρ is the density of mobile dislocations, t_f is the flying time of dislocations on the distance L between the obstacles (i.e. forest dislocations in the case of *fcc* metals) and b is the magnitude of the Burgers vector of dislocation. The waiting time, t_w is related mainly to the interaction of mobile dislocations with both forest dislocations and the solute atoms as well as with the activation energy Q for the obstacle overcoming.

The second important parameter is the critical strain, ε_c, at which the PL effect is beginning. Then the waiting time t_w reaches the value of ageing time t_a and all the so far active dislocation sources are locked by solute atom atmospheres $(t_w \gg t_f)$. The critical strain ε_c may be then expressed by the well known general expression (see e.g. [2]):

$$(\varepsilon_c)^{m+\beta} = A\dot{\varepsilon}\exp(E_m/kT), \tag{2}$$

where A is a constant and E_m is the migration energy of the vacancy. Equation (2) is in good agreement with most experiments and the $(m+\beta)$ values are between 2 and 3 for substitutional, and between 0.5 and 1 for interstitial alloys, respectively.

The main aim of this work is the confirmation of the anisotropic behaviour of the PL and AE effects reported at the first time in [6, 10]. In this paper the attempt to explain the correlations between the AE and PL effects has been also curried out.

2. Experimental procedure and results

The tensile tests were carried out with tenfold plane specimens using the standard INSTRON-6025 type machine. In each test the rate of the traverse of testing machine was 2 mm/min. The two series each of five specimens were examined. The first one of polycrystalline α-brass CuZn30, obtained by HCC technology (Horizontal Continuous Casting), were tested by applying the so far used AE analyser, and the second series of the samples of polycrystalline aluminium alloys of PA11 type were tested by applying of new AE analyser. The samples in each series were obtained by cutting from the sheet along the directions forming the following angles: 0°, 22.5°, 45°, 67.5° and 90° with respect to the rolling direction. Each specimen was of the gauge length $l_0 = 90$ mm (overall length $l_c = 105$ mm), $b_0 = 20$ mm width and $a_0 = 3.50$ mm thickness.

For each testing sample, simultaneously with the measurement of the external tensile force, the basic AE parameter, i.e. the rate of AE events, $\Delta N_z/\Delta t$, was continuously detected. Other important parameters of an older type of AE measuring system were: total amplification 88 dB, threshold voltage 1.21 V, and the broad-band piezoelectric sensor which permits to detect the AE pulses within the range from 100 to 1000 kHz; for more details see also [10–13]). On the other hand, using a new AE analyser, the RMS voltage parameter of AE signal was additionally measured; for many other possibilities of a new analyser see also in our other paper in this issue [15].

Figure 1 shows the AE behaviour, external force and the total sum of AE events in the CuZn30 samples cutting at the angle $\beta = 22.5°$ for which the critical strain ε_c is minimal (Fig. 1a) and the total sum of AE events $\Delta\Sigma_c$ reaches a maximum (Fig. 1b) in the respect to the AE behaviour for other cutting angles (not presented here; for more details see [10]). This means that the PL effect exhibit some anisotropic property. The anisotropic behaviour of the PL effect is visible also in Fig. 2 and 3 where, similarly, but for the PA11 type of samples, the AE behaviour (Figs. 2b, c) and the external force (Fig. 2a) are illustrated for such a cutting angle at which the both AE activity and the drops of external force are maximal. This is clearly visible when comparing Fig. 2a and Fig. 2b, respectively, with corresponding Fig. 3a and Fig. 3b, where the mentioned quantities are minimal. However, in the case of PA11 alloys the maximum of the total sum of AE events is displaced to the angle $\beta = 45°$. It is visible in the Table 1, where also the results for PA2 alloy are presented, firstly, to compare with other results and, secondly, to show that the anisotropic properties of PL effect in PA2 aluminium alloys are maximal also for $\beta = 22.5°$, thus similarly as in the case of CuZn30 alloys.

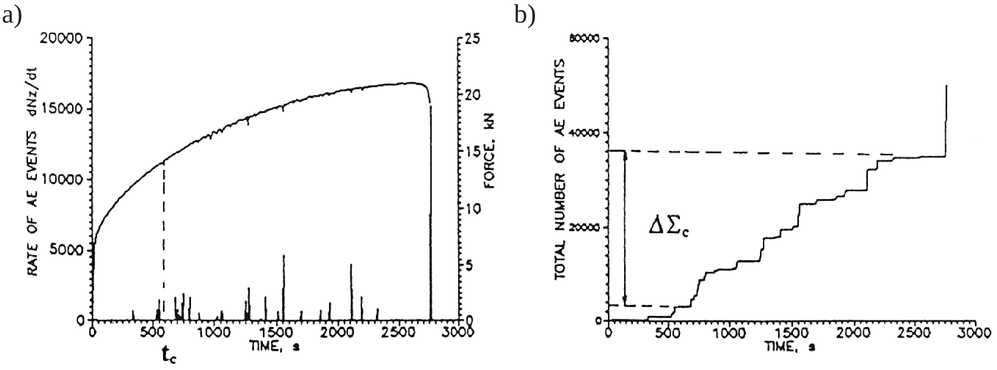

Fig. 1. EA and PL phenomena (a) and the corresponding sum of AE (b) in polycrystalline α-CuZn30 brass specimens cutting at the angle $\beta = 22.5°$.

One can see that the anisotropic property appears at the different angles for various materials, even for the same material but obtained using another technology, as in the case, for example, the α-brass CuZn30 samples obtained by conventional technology [10], where the maximal anisotropy was observed at the angle $\beta = 67.5°$. The explanation of the anisotropic behaviours of AE and PL effects will be possible after the detailed analysis of the texture of theses materials. This problem is one of the important part of the actually realized research project financed by the Scientific Research Committee (grant No. 3 T08A 032 28).

Table 1. The influence of the specimen orientation on the total sum of AE events for PA11 and PA2 aluminium alloys during the PL effect.

Orientation (cutting angle β)	0°	22.5°	45°	67°	90°
Total sum Σ_c for PA11	3400	3500	8020	2520	4500
Total sum Σ_c for PA2	7600	22000	448	9500	2400

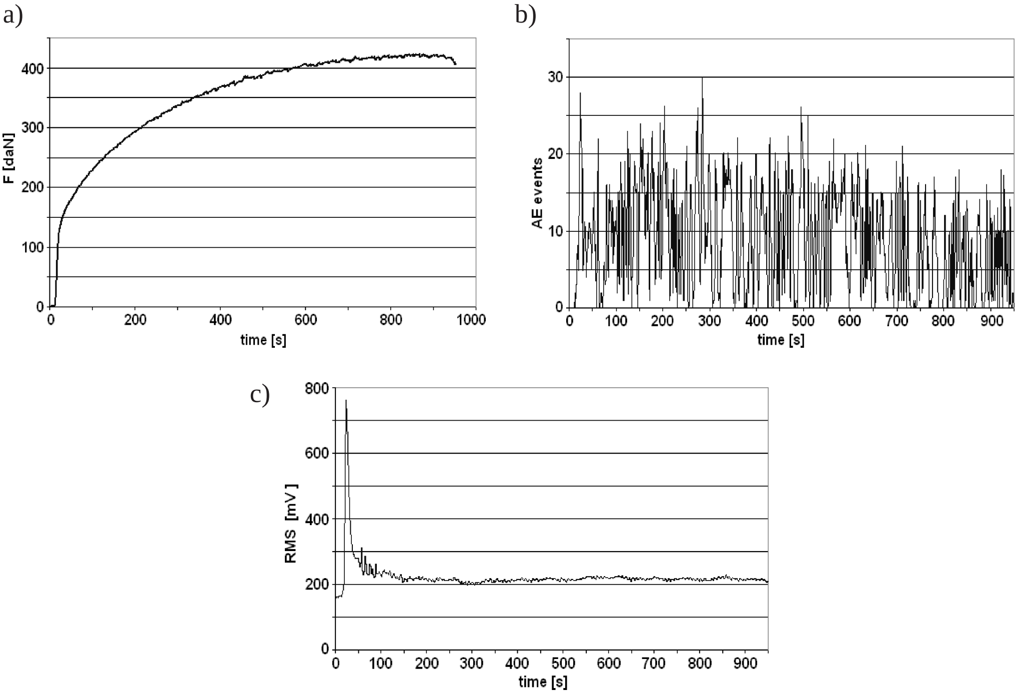

Fig. 2. The external force (a), the rate of AE events (b) and the RMS (c) parameters during tensile deformation of PA11 sample cutting at the angle $\beta = 45°$ in respect to the rolling direction.

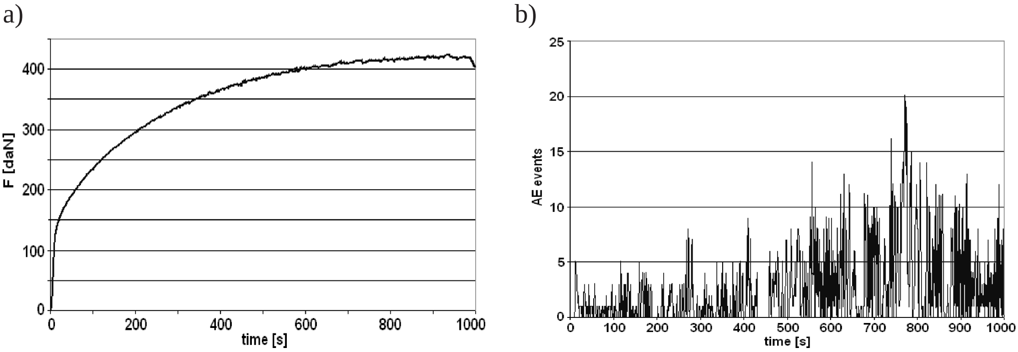

Fig. 3. The external force (a) and the rate of AE events (b) during tensile deformation of PA11 sample cutting at the angle $\beta = 67.5°$ in respect to the rolling direction.

3. Discussion

Two main concepts of AE sources can be considered. First, according to the ESHELBY theory [3], says that the vibrating (or accelerating) dislocation kink generates the acoustic waves, and the rate, P, of the acoustic energy radiation is given by:

$$P = \gamma m \langle (\mathrm{d}v/\mathrm{d}t)^2 \rangle, \tag{3}$$

where v is the kink velocity, γ is a constant and m is the kink effective mass. Second one says, according to the NATSIK and CHISHKO theory [7], that the acoustic energy, E, released due to the annihilation of two opposite dislocations is given approximately by:

$$E = MV^2/2, \tag{4}$$

where M is the effective mass of dislocation unit length and V is the relative velocity of dislocations before annihilation. The same formula can be used in the case of the escape of dislocations from the specimen to its free surface. The physical nature of both PL and AE phenomena is very similar and it is related to the dynamic dislocation-dislocation interaction (processes of collective acceleration and annihilation) as well as to the dynamic interaction of diffusing solute atoms and the mobile dislocations, thus in agreement with the old Cottrell idea that the PL effect begins at the strain ε_c for which the solute atoms can form atmospheres around the mobile dislocations locking them efficiently, and after the unlocking the process is repeated.

We can discuss the obtained results using the propositions presented in our earlier papers [11, 12], in which it has been suggested that the contributions to the measured AE signals are the dislocation acceleration and mainly the surface annihilation of dislocations. In the case of a PL effect, the AE activity takes place nearly at the beginning and it is hold in the whole range of PL deformation (Fig. 1a, 2b and 3b).

Below, we show that such an AE behaviour is in agreement with the simple dislocation dynamic model of PL effect [13], proposed earlier by one of the authors. According to this model, each drop of the external force, appearing on the force-time curve, is related to the unlocking of the dislocation sources within some localized place of the sample, where simultaneously a high stress concentration is formed. The next dislocation sources become unlocked due to the transmission of the stress concentration which leads to high dynamics of the generated dislocations. In consequence, a deformation band is formed and propagates up to the time moment when the waiting time, t_w, again reaches the value of the ageing time t_a. The strain rate in the deformation band, $\dot{\varepsilon}_d$, is now greater than the strain rate $\dot{\varepsilon}$ given by Eq. (1) due to the effect of high dynamics. In this way the drop of external load appears on the force-time curve since, according to the Penning equation:

$$K^{-1}\mathrm{d}\tau/\mathrm{d}t + \dot{\varepsilon}_d = \dot{\varepsilon} \tag{5}$$

we have $\mathrm{d}\tau/\mathrm{d}t < 0$ for $\dot{\varepsilon}_d > \dot{\varepsilon}$; K is the stiffness coefficient of the tensile system.

The high dislocation dynamics means also that they can resolve great accelerations due to the dislocation-dislocation interaction, giving thus the contribution to the AE peak, generally, according to Eq. (3). The annihilation of the dislocation segments, when the dislocation loops are broken off from the Frank-Read source gives the contribution to the AE peak, generally, according to formula (4). However, the contribution due to the annihilation is greater than the one due to the acceleration, since the former is strongly enhanced by the surface annihilation of dislocations as in the case of the steps creation due to the slip lines and slip bands formation which is a quite efficient [11, 12] source of AE events, generally also according to the formulae (4). Moreover, it is interesting to note that this supposition is quite compatible with the results of the paper [5], where the role of the surface in the AE phenomenon during plastic deformation of metals is clearly evidenced.

A more detailed discussion of the problem of the anisotropy of AE and PL phenomena, based on texture analysis carried out for all cutting angles and for various aluminium alloys, is considered in the framework of the mentioned grant and will be successively presented in further papers.

4. Conclusions

1. The enhanced AE activity has been observed in both CuZn30 α-brass and PA2 aluminium alloy samples at the cutting angle 22.5° and in PA11 aluminium alloy samples at the angle 45° between the specimen axis and the rolling direction.

2. The anisotropy of the PL and the AE effects is related with the maximal value of the total sum of AE events and the maximal drops of the external force.

3. The correlations between the jerks of external load and the peaks of AE may be interpreted on the basis of the dislocation models of AE source in terms of elementary dislocation annihilation and acceleration processes.

4. The proposed interpretation of the AE behaviour is in good agreement with the simple model of the PL phenomenon.

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