A CRITICAL ANALYSIS OF THE SERRATED FLOW OF PORTEVIN - LE CHATELIER EFFECT

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Abstract

Plastic instabilities associated with the Portevin - Le Chatelier (PLC) effect will be examined with special attention to relaxation oscillations behaviour. The types of serrations are studied and interpreted in terms of a constitutive flow model which takes into account stress dependent changes accompanying a strain rate changes. The experimental data in aluminium - magnesium industrial dilute alloys are discussed in the light of the present study and a new analysis vision of PLC effect is proposed. Emphasis is put on the connection between the different types of instabilities and the relaxation oscillations behaviour. The spatial correlation in the case of A and B types of PLC instabilities is investigated and discussed with reference to A9G5 alloy.

***Key words**: Plastic instabilities, Portevin - Le Chatelier effect, relaxation oscillations, deformation bands, spatial correlation.*

Résumé

Les instabilités plastiques associés au phénomène Portevin - Le Chatelier (PLC) seront examinées avec une attention particulière au cycle d'oscillations de relaxation. Les différents types de décrochements de contrainte sont étudiés et interprétés grâce à un modèle d'écoulement plastique qui prend en compte la dépendance contrainte-vitesse de déformation. Les données expérimentales dans des alliages industriels dilués Al-Mg sont discutés à la lumière de la présente étude, une nouvelle vision d'analyse de l'effet PLC est ainsi proposée. L'accent est mis sur la relation entre les différents types d'instabilités et le cycle des oscillations de relaxation. La corrélation spatiale dans le cas des instabilités PLC de types A et B est examiné et illustré par un exemple de l'alliage A9G5.

***Mots clés**: Instabilité de la plasticité, effet Portevin-Le Chatelier, oscillations de relaxations, bandes de déformation, corrélation spatiale.*

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ملخص

تـتم دراسـة إرتـباط اللاإسـتقرار فـي التشـوه اللـدن بظاهرة Portevin –Le Chatelier (PLC) مع التركيز خاصـة علـى سلوك دورة الإهتزازات المتراخية. ستدرس مختلف أنـواع فك الإجهـاد و تعلـل إعـتمادا علـى نمـوذج الإنسياب اللدن الذي يأخذ بعين الإعتبار تبعية الإجهاد بسـرعة التشـوه. سـنناقش، علـى ضـوء هـذه الدراسـة، المعطيات التجريبية الخاصة بالسبائك الصناعية Al-Mg و بالتالـي سنقترح رؤيـا جديدة لتحليل تأثير PLC. هناك تأكيد علـى العلاقة بين مختلف أنواع اللاإستقرار و دورة الإهتزازات المتراخية. سيتم فحص الصلب المكانية في حـالات اللاإستقرار PLC نوع A و B، و ستوضح بمثال خاص بالسبيكة A9G5.

***كلمات المفتاح:** الإستقرار في التشوه، ظاهرة Portevin –Le Chatelier (PLC)، الإهـتزازات المتراخـية، شرائط التشوه المحلي، الترابط المكاني للشرائط.*

Among the various plastic instabilities that a solid can undergo, the Portevin - Le Chatelier (PLC) effect, associated with inhomogeneous and nonuniform plastic flow, is the best well-known to metallurgists. It consists in repeated formation and, sometimes, propagation of deformation bands along the specimen. This is accompanied by the appearance of abrupt stress drops or steps on the deformation curves. Because of the rapidly increasing importance of this field, we have included this study to investigate the analysis of localised deformation.

In a great number of dilute alloys plastic instabilities of PLC effect are observed under suitable conditions of temperature and applied strain rate. It has been well established that this phenomenon is accompanied by inhomogeneous deformation of the specimen [1-7]. From the technical point of view of materials design, plastic instabilities leading to strain localisation are most important as they influence the workability, the ductility and the service life of materials. To date the PLC effect has been observed in a great number of dilute interstitial and substitutional alloys on Al, Cu, Ni, Fe, etc. basis (in polycrystalline form for the most part).

EXPERIMENTAL

Flat tensile A9G5 specimens, width 5mm, were cut parallel to the rolling direction. They were tested in the as received condition, in a hard tensile system with the effective elastic modulus M ≈ 3.10^4 MPa. PLC instabilities were found at 300 K in the range 10^{-6} s^{-1} ≤ $\dot{\varepsilon}$ ≤ $2,5.10^{-2}$ s^{-1} and evidenced by the initiation of inhomogeneous plastic flow on reaching a critical strain. The inhomogeneous yielding is characterised by the repeated initiation and sometimes propagation of bands along the specimen gauge length for the duration of the test. Three possible types of serrations on the deformation curves (usually labelled A, B and C) are recorded (fig. 1). They correspond to three different types of deformation band behaviour, we shall designate the type of a band by the corresponding serration type [1, 3].

With periodic type A jerks ($\dot{\varepsilon}$ > 10^{-3} s^{-1}) successive bands initiate at the same end of the specimen and travel along the gauge length in the same direction. Type B yielding occurs at intermediate strain rates (10^{-5} s^{-1}< $\dot{\varepsilon}$ <10^{-3} s^{-1}) the bands may propagate discontinuously in jumps along the specimen. Type C yielding corresponds to low strain rates ($\dot{\varepsilon}$< 10^{-5} s^{-1}); the first band always initiates near one of the specimen shoulders while further band initiation takes place rather at random within the specimen.

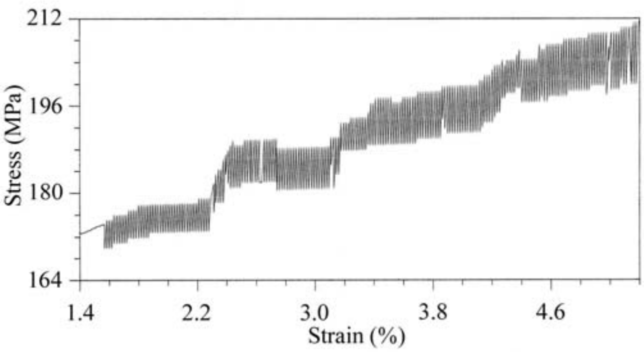


Figure 1: Example of plastic deformation curve, under constant strain rate, of type B instabilities (Flat tensile Al-5052 specimens, width 6mm, $\dot{\varepsilon}$= $2,8.10^{-5}s^{-1}$ at 300 K, after [5]).

CLASSIFICATION OF PLC BANDS

From the experimental results, it appears that during type A serrated yielding the band width decreases with increasing strain rate and decreasing amplitude of instabilities. The periodical sharp serrations mark the initiations of the successive bands. Irregularities in the stress vs. time curve correspond to variations in this propagation velocity associated with local surface imperfections or with the reflection of the front at the specimen ends. It has been demonstrated that the band width does not decrease below a minimum value ≈ 0.5 mm. The transition from type B into type A does not take place before the band has attained this minimum width. During type C serrations it is impossible to determine exactly the band width. In this region indeed it was possible to determine the distance of the hops made by the band during the load drops [1, 2], and changing the stiffness of the tensile system has a strong influence on the distance of the hops [8-10]. It is concluded that type A serrations are associated with a smooth continuous propagation of a deformation band from one end of the specimen to the other. The fine undulations can be attributed to the initiation of a new band, usually at one of the grips; the wavy line between them represents the propagation along the specimen. A corresponding fast succession of spatially correlated band initiation events gradually takes a form of a continuously propagating deformation front.

On type B, one part of serration corresponds to the elastic line of the tensile system the other part corresponds to the rapid load drop. It follows that this kind of serrations is accompanied by an alternating process of increasing elastic strain in the entire specimen and a rapid local plastic deformation in a band. Usually the band moves forward with little hops which coincide with the load-drops and plastic deformation of the whole specimen is achieved by "correlated hopping" of the band along the specimen. The time between two successive load drops being the time between two successive "hops" of the band.

The reloading sequence of type C serrations can be partly plastic followed by a rapid load drop. The band files by a discontinuous manner and "uncorrelated hopping" aspect is recorded. Type C stress drops resemble type B serrations in their appearance and in fact appear sometimes in series in the same shape as type B. Each packet of serrations on the stress vs. time curve corresponds to one such sequence of bands filling up the entire gauge length of the specimen and the number of PLC bands formed corresponds to the number of serrations. This apparent change in the type results from the influence of ageing of the temporarily halted dislocation and recovery in the band front. In all cases the observed starting points of fresh bands could be understood in these terms [1-3] .

The ageing phenomenon which gives rise to serrations was examined by measuring the increase in serration height, $\Delta\sigma$, which increase in temperature and reloading time. At a fixed temperature and at a constant strain rate, the reloading time between jerks, Δt, is constant. Increasing the strain rate decreases the reloading time between jerks, in fact $\Delta t \; \alpha \; \dot{\varepsilon}^{-1}$; and from a $\dot{\varepsilon}$ vs. 1/T graph [3, 11], it has been concluded that $\dot{\varepsilon}$ increases with increasing temperature according to $\dot{\varepsilon} \propto \exp(-Q/kT)$, where Q represent the activation energy for the ageing process, T the absolute temperature and k the Boltzmann constant. As underlined by [3], these observations offer a convenient means for studying the temperature dependence of jerk type and, in our case, a response to the transition B - C types and A - B types with increased temperature or reloading time (decreased applied strain rate), this is summarised by table 1.

$\dot{\varepsilon}$(s^{-1})	300 K	350 K	430 K
10^{-5}	C	no jerks	no jerks
10^{-4}	B	C	no jerks
10^{-2}	A	B	C

Table 1: Transition of serrations types as a function of temperature and strain rate (e.g. for $\dot{\varepsilon}$= 10^{-5} s^{-1} and at 350 K, the deformation regime is homogeneous and uniform).

Physical model of the PLC effect based on local constitutive equations [12] predict periodic bursts of the plastic strain rate to which the loading system responds with stress drops. Where the entire specimen deforming coherently, all cross sections performing such relaxation oscillations in a concerted way, periodicity of stress drops would be preserved. On the basis of the model [13] at a constant applied strain rate, the dynamic curves $\sigma(\dot{\varepsilon})$ of figure 2 represent schematically the correspondence between types A, B and C serrations and the relaxation oscillations for each type. The emphasis is put on fine undulations (type A), the elastic (type B) and plastic (type C) parts of jerks on one hand, and the corresponding spatial organisation and kinetics of bands on the other hand [1,2]. It has been pointed out, however, that an annealed Al-Mg dilute alloys specimens exhibit a regime of plastic deformation associated to PLC effect in which there coexist temporal instability and spatial stability on macroscopic scale. In this regime discontinuous plastic flow occurs uniformly along the entire gauge length of a tensile specimen, without spatial localisation.

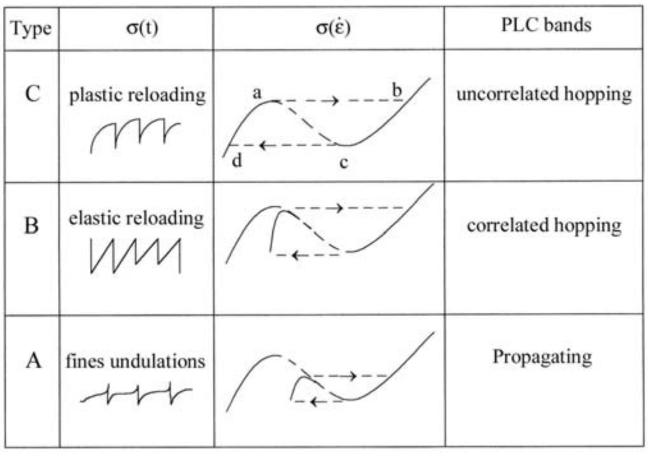


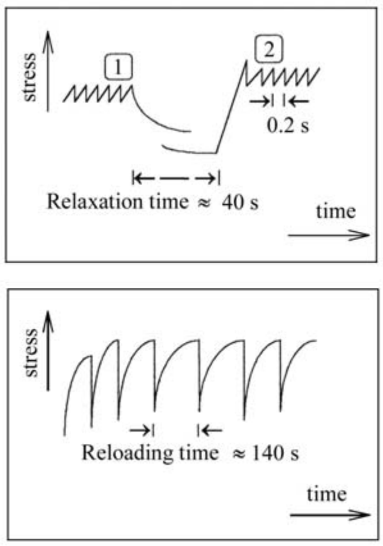
Figure 2: Schematic representation.
Overview of plastic localisation of PLC effect. The variation of the strain rate is described by cycles such as "abcd" on type C, type B and type A serrations. Relaxation oscillations behavior consisting in strain rate jumps a → b and c → d and continuous variation of $\dot{\varepsilon}$ along the ascending branches d - a and b - c of the σ( ) characteristic.

RELAXATION OF SPATIAL CORRELATION

Experiments show that it is possible to break the spatial correlations in the case of A or B type of PLC bands (e.g. local surface imperfections [1]). In these experiments, band propagation is stopped by unloading the specimen. The behaviour upon further reloading depends on the hold time under zero stress. If the latter is smaller than a critical value (≈ 5 s), which corresponds to a strain rate about 10^{-4} s^{-1}, band propagation resumes from where it was stopped. If it is larger, the band front is so well locked that an other band (the secondary band) is initiated at the other head of the specimen. In parallel, a yield point whose magnitude increases with the hold time is recorded when the specimen is reloaded (fig. 3a). This indicates that dislocations are pinned again by the solute atoms during the static ageing sequence.

In some experiments the specimen surface was also be repolished during the ageing to remove all stress concentrations, but no noticeable difference was found with respect to non repolished specimens. Since couplings of mechanical origin can hardly relax with a characteristic time and since the surface condition appears to play no role in this braking of the spatial correlation, these results have been considered as a proof that band propagation requires fresh dislocation to be available at the band front and that the spatial couplings have a microstructural origin. At least, it could be useful to further investigate this type of situation, and perhaps to reinterpret it, particularly in the case of PLC bands.

PLC bands of type C, which occur at low strain rates and high temperatures deserve further examination because their occurrence is not spatially correlated as they appear at random places on the specimen length. They also correspond to conditions where the amplitude of instabilities (magnitude of the load drop, band width) is maximum [1, 2]. The reason for this loss of correlation is apparently the same as in the previously reported experiments, except that the relaxation of the coupling takes place during the reloading sequence between two load drops (fig. 3b). At low strain rates this reloading time is maximum, of the order of several hundreds of seconds. One can therefore define again a critical time for the breaking of the spatial correlations, which must be a thermally activated quantity since type C bands are also observed at high temperatures and with smaller reloading times.



(a)

(b)

Figure 3: Fragments of stress vs. time curve: **(a)** type B serrations, **(b)** type C serrations, for A9G5 in a flat specimen (width 5 mm), under constant strain rate, at 300 K.
(a) Static ageing experiment during relaxation of stress test: type B bands ($\dot{\varepsilon}$ ≈ 2,5.10^{-4} s^{-1}) 1 and 2 denote the primary and the secondary band obtained after static ageing (≈ 40 s), respectively.
(b) Spatially uncorrelated type C bands during reloading test ($\dot{\varepsilon}$ ≈ 5.10^{-6} s^{-1}).

CONCLUDING REMARKS

A systematic change of the serration type from A to B to C is found to follow an increase in the strain rate with temperature. It has been pointed out that each type corresponds to a special way of inhomogeneous deformation. The mechanisms by which the band propagates from one section to another were interpreted as follows: the material near the grip where the first band ended had been aged least and therefore this grip will be the preferred place for the start of the second band.

Upon further consideration, the spatial correlation between successive bands disappears with the type C serrations, where the reloading time is larger than a few seconds and a relaxation stress appears at the front of the band. Most probably, the mechanism responsible for this relaxation is not related to dislocation repining, since the dislocation waiting times (typically of the order of a few seconds) seem to be much smaller than the critical times. Therefore, the transition from continuous (correlated bands) to serrated yielding (uncorrelated bands) may alternatively rationalised in terms of the occurrence of dynamic recovery mechanism which seems to be active at the band front at low strain rates.

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