CONTRIBUTION TO THE STUDY OF PORTEVIN-LE CHATELIER EFFECT IN ALUMINUM ALLOY 2024

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Abstract

Aluminum alloys are susceptible to the Portevin-Le Chatelier (PLC) effect. This phenomenon, particularly well-studied in Al-Mg alloys, is associated with deformation bands that leave unwanted marks on the surface of sheet products after deep drawing, thus restricting their commercial applications. Moreover, the PLC effect is harmful for formability because the PLC bands can lead to a premature onset of necking and fracture.

Heat treatments, performed on Al-Cu alloys to reach the required mechanical properties, influence the PLC effect of those alloys. Actually, Al-Cu alloys can exhibit on their surface unevenness associated with the serrated yielding phenomenon or PLC effect during plastic deformation.

Among various experimental approaches to study the aging process, electrical conductivity and acoustic emission are often used. Plastic deformation generates continuous acoustic emission that reaches a maximum at or near the yield stress and decreases with work hardening, due to the motion of dislocations. There is an obvious relationship between the shape of the count rate versus strain rate curve and the microstructure developed in the alloy during aging.

Introduction

"The Portevin-Le Chatelier (PLC) effect" is a typical plastic deformation observed in face-centered cubic metallic alloys such as aluminum alloys. The high mobility of dislocations under certain conditions of temperature, strain rate and deformation is responsible of the creation of an instable plastic flow [1]–[4] that results in serrations on the stress–strain curves [4]–[7]. Those heterogeneities and defects can be observed on the surface of the deformed material in an oblique band structure [4], [6]–[8]. The necessary strain for the appearance of PLC effect is the plastic critical strain ε_c [8], [9]. The generally accepted theoretical interpretation of the PLC effect is the dynamic strain aging (DSA) that consists of a dynamic interaction between mobile dislocations and solute atoms [2].

In Al–4 wt.%Cu alloys, the diffusion rate of substitutional solute atoms is very low at room temperature. However, when plastic deformation or quenching is applied, some vacancies required for diffusion are produced. The rate of diffusion may thus increase sufficiently to cause strain

aging during plastic deformation [5]. To delay the onset of the PLC effect, the formation of GP zone during aging treatment appears to be very effective [7].
Three types (A, B and C) of PLC serrations can be clearly observed in aluminum alloys [6], [9], [10]. Type A bands appear at large strain rates ($\geq 5\times10^{-3}$ s^{-1}), type B at intermediate strain rates ($\geq 10^{-4}$ s^{-1} and $\leq 10^{-3}$ s^{-1}) and type C at very low strain rates ($< 5\times10^{-5}$ s^{-1}). On the stress-strain curve, type A is characterized by weak undulations and a continuously propagating deformation front, type B by regular seriations and discontinuous moving bands, and type C by more marked seriations and stochastically bands nucleation [4], [8]. The main factors that influence the type of bands are imposed strain rate and testing temperature: a decrease in strain rate or an increase in testing temperature implicates a change from type A to type B and to type C [4], [8]. In Al-4 wt.% Cu alloys, for type A, at large applied strain rate, the mobility of solute diffusion is too slow to catch up with the fast dislocation motion and the weak DSA effect causes slight fluctuations on stress curves. For types B and C, at lower applied strain rates, the unpinning process of thermally aged dislocations, which causes the enhanced DSA effect, is responsible for stronger seriation on stress curves [8]. From conventional strain-stress tensile curves, the parameters used to characterize the PLC effect are the stress drop of serrations ($\Delta\sigma_D$, stress difference between the highest and lowest points of a serration step) and the reloading time of serrations (Δt_R, time needed for the reloading process) [11], [12].
The acoustic emission (AE) method can be used to study the PLC effect in dilute alloys. The AE signal is composed of discrete bursts associated with the motion of large dislocation ensembles leading to stress seriations, which are surimposed on continuous AE generated during macroscopically smooth plastic flow [13].
This paper presents additional work done from a previous study [14]. Heat treatments are carried out between room temperature and 100°C. Non-destructive methods such as acoustic emission and electrical conductivity are used to study the “Portevin-Le Chatelier (PLC)” effect and the kinetics of precipitation hardening process.

Materials And Methods

Samples were cut from AA2024 sheets (1.6 mm of thickness) with dimensions of 40X40 mm for hardness measurements and 200X40 mm for tensile tests (parallel to the rolling direction). The chemical composition of AA2024 is given in table I.
Solution treatment was following: heating at 495 ± 5°C during 40 minutes with immediate water quenching. After solution treatment, some samples were kept at -40°C to stop their microstructure evolution. Natural aging treatment was applied to some samples to reach the T4 temper. Accelerated aging treatments at temperatures higher than room temperature (RT) but lower than 100°C (i.e. 35°C, 50°C and 70°C) were also performed on some specimens.
The macrohardness was measured using an Emco M4U-02 hardness tester with a Vickers indenter using a load of 30 kgf with a minimum of five measurements per test.
Tensile tests were performed at room temperature on an INSTRON 4505 apparatus with an imposed deformation rate (2 mm/min) until rupture (l_0 = 80 mm).

During tensile tests, the acoustic emission (AE) was monitored. The transducers were resonant R15 Alpha type. The AE signal was amplified by a preamplifier set at a gain of 25 dB. The acquisition system (AEWIN DISP rev.1.82.) was controlled by a computer.
Electrical conductivity measurements were performed using an SIGMACHECK 2 eddy current conductivity meter after calibration at room temperature.

Table I. Chemical composition of the AA2024 in wt.%

Element (wt.%)							
Cu	Mg	Mn	Fe	Si	Cr	Ni	Al
3.98	0.77	0.61	0.22	0.01	0.05	0.01	balance

Results And Discussion

Electrical Resistivity

As shown on figure 1, hardness and electrical resistivity present a similar kinetic evolution. This means that the mechanisms leading to hardening also cause the variation of electrical resistivity, and that the sharp increase of electrical resistivity observed at RT can be linked to the formation of S''-phase and S-phase [14][15]. This non-destructive technique can thus be used to study the evolution of precipitation hardening process.

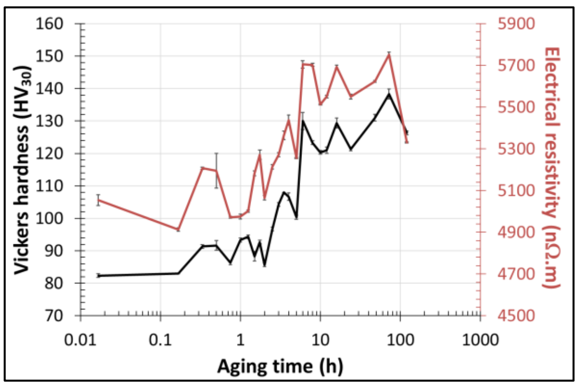

Figure1. Kinetic evolutions of hardness and electrical resistivity during natural aging treatment

Portevin-Le Chatelier (PLC) Effect

Tensile Test. During tensile tests at a nominal strain rate of 4.14×10^{-4} s^{-1}, instabilities are observed on samples aged at room temperature for various times (Figure 2). Those heterogeneous plastic flows correspond to the "Portevin-Le Chatelier effect". The plastic onset strain for serration, ε_c, increases with the natural aging time. From Figure 3 (that is a magnification of Figure 2), the type of instabilities for natural aging until 8 hours is type B. For aging times longer than 12 hours, the amplitude of seriation strongly decreases and PLC effect is no longer observed. It can also be seen that the onset deformation value for serrated flow increases with aging time. No PLC effect is observed for ageing treatment at 35, 50 and 70°C regardless of the duration of the treatment.

$\Delta\sigma_D$ and Δt_R were calculated for the W state and for natural aging at times shorter than 8 hours. The results are given in table II and confirm that type B PLC effect is observed in those samples.

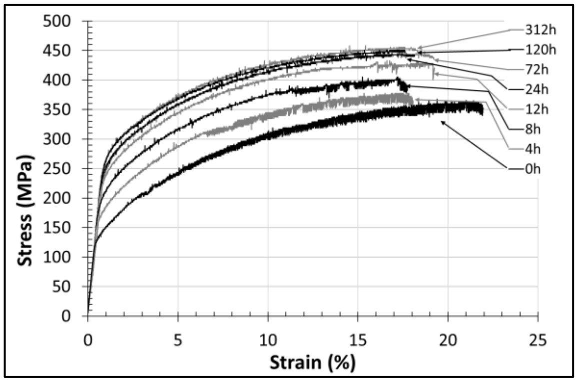

Figure 2. Stress-strain curves of AA2024 alloy after various times of natural aging treatment

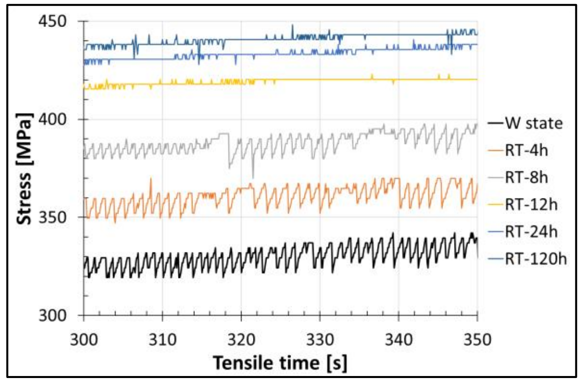

Figure 3. Magnified images of tensile curves of AA2024 alloy after various times of natural aging treatment

Table II. Stress drop of serrations ($\Delta\sigma_D$) and reloading time of serrations (Δt_R) calculated for tensile curves of figure 3.

T4 treatment duration	W state	4 hours	8 hours
$\Delta\sigma_D$ (MPa)	10-17.5	12-15.5	7.5-10
Δt_R (s)	~1	~1	0.5-1

Acoustic Emission. As PLC effect is a plastic deformation characterized by a high acoustic emission corresponding to stress release during serrated flow, recording of acoustic emission (AE) during tensile tests will allow ensuring that the observed instabilities are really due to PLC effect. Samples in the W state, after aging treatment at RT during 5 and 120 hours, at 50°C for 24 hours and at 70°C for 8 hours were tested.

Results obtained for samples in the W state (Figure 4a) and after 5 hours of natural aging (Figure 4b) confirm the presence of PLC effect: very energetic acoustic emission is recorded at the time of serrated flow. Moreover, in the case of W state samples, a peak of AE is observed at yield stress (Figure 4a – green circle) that disappears for the others aging conditions. This event is in concordance with a high noise amplitude (Figure 5a). Actually, in Al alloys, AE intensity decreases with aging and peak AE intensity at yield decreases by more than a factor 3 from the W state to the fully aged state [16]. After natural aging for more than 5 hours or a treatment at 50°C (Figure 4c) and 70°C, the emission counts due to the PLC effect disappear.

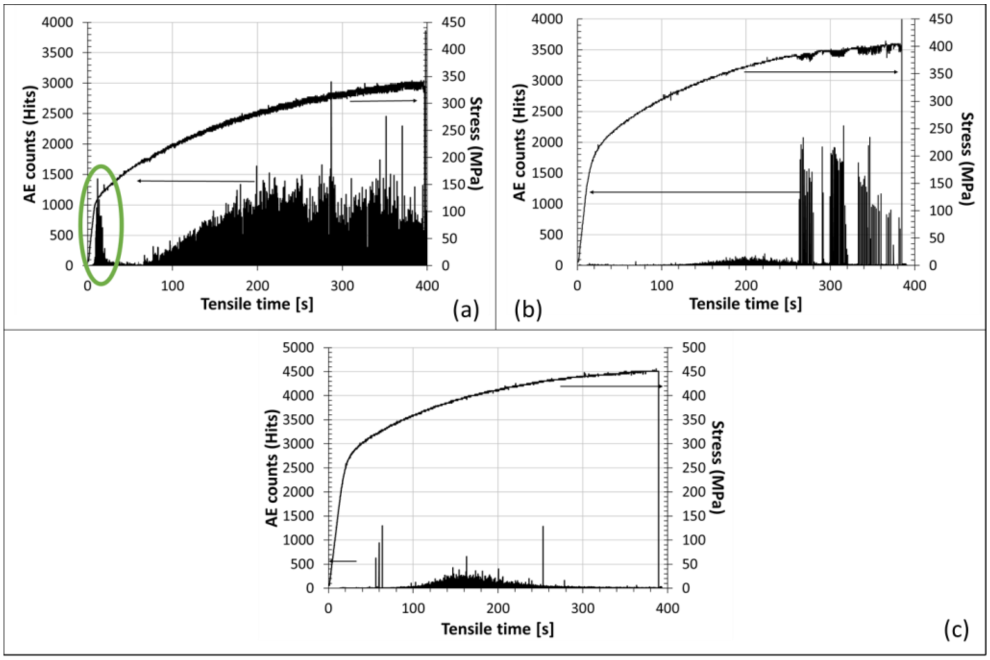

Figure 4. Tensile curves and recording of the acoustic emission during tensile test for AA2024 (a) in W state, (b) after 5 hours of aging at RT, (c) after 24 hours of aging at 50°C

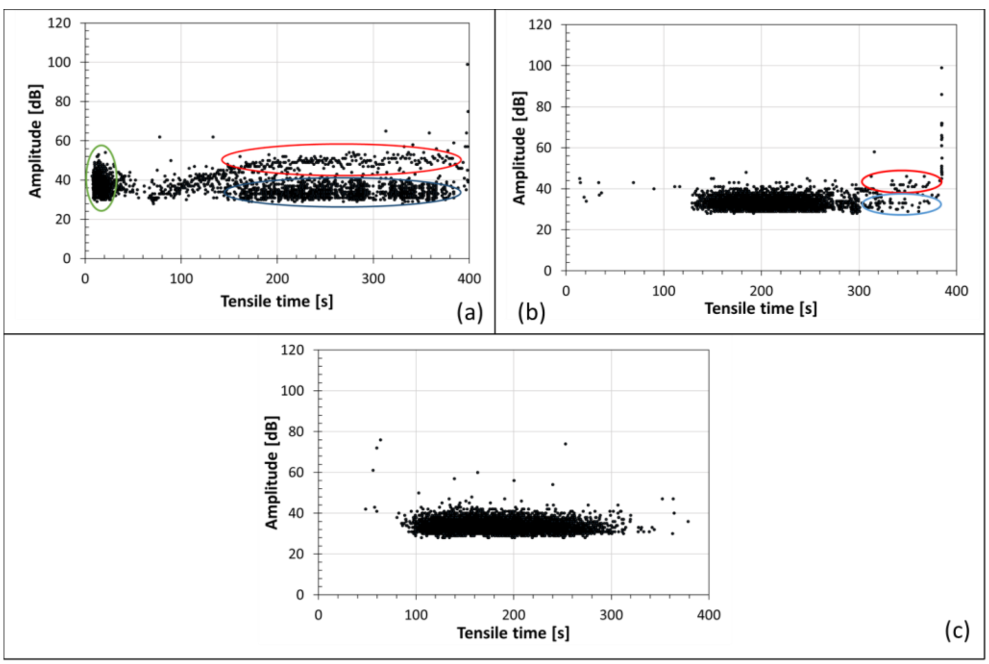

Figure 5. Recording of noise during tensile test of AA2024 alloy (a) in W state, (b) after 5 hours of natural aging, (c) after 24 hours of aging at 50°C

In the W state (Figure 5a) and after a natural aging for 5 hours (Figure 5b), the noise recording shows two levels of amplitude after about 3 min and 5 min: a higher one and a lower one. Those two levels are not found in AA2024 samples aged at 50°C for 24 hours (Figure 5c).
In W state, the time analysis of the acoustic activity (Figure 6) highlights the existence of three major stages during tensile test. The first one corresponds to the yield stress (Stage I), the second one to the plastic deformation due to tensile test (Stage II) and the third one to the PLC effect (Stage III). After aging at 50°C during 24h, only stage II is present due to the precipitation process that blocks the motion of dislocations. After aging at 50°C during 24h, only one stage is present.

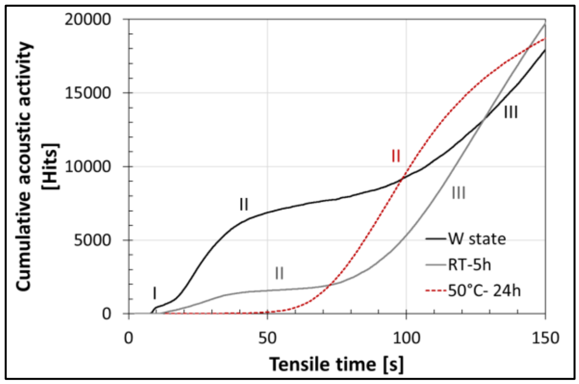

Figure 6. Evolution with aging treatment of acoustic activity of AA2024 alloy during tensile test

Electrical Resistivity. As electrical resistivity evolution is an efficient experimental approach to study the aging process of aluminum alloys, this technic could also be efficient to identify PLC effect in dilute alloys because of the formation of localized deformation bands.
The evolution of electrical resistivity during tensile test at RT on W state samples and after 24 hours of aging at 50°C is presented on figure 7. A continuous increase in electrical resistivity with time during tensile test is observed due to the increase in defects number inside the material. This increase seems to be linear in the case of a sample heat treated during 24 h at 50°C. Bigger fluctuations can be observed for W state sample after about 60s of tensile test, and they increase after about 280s of tensile test. Those fluctuations can be linked to the evolution of the acoustic emission during tensile test (Figure 8). To highlight differences during tensile test, the conditions of electrical conductivity measurements must be optimized.

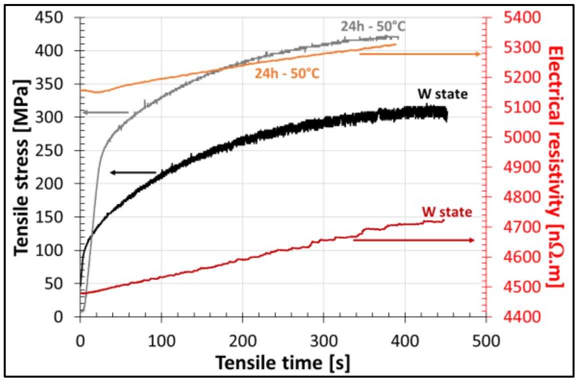

Figure 7. Evolution with tensile test of electrical resistivity of AA2024-W and after 24 hours of aging at 50°C

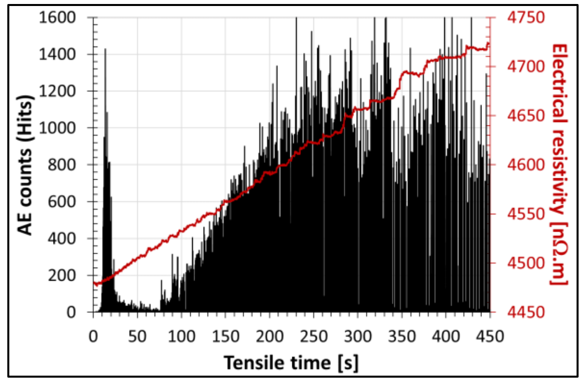

Figure 8. Evolution with tensile test of acoustic activity and electrical resistivity of AA2024-W

Conclusion

The kinetics of the aging process and the appearance and disappearance of "Portevin-Le Chatelier (PLC) effect" in AA2024 aluminum alloy were studied. Here are the conclusions of this study:

1. The mechanisms of hardening are responsible for the variation of electrical resistivity and induce a sharp increase of electrical resistivity during treatment at RT.
2. The instabilities observed on tensile test curves for samples aged at RT for various times are heterogeneous plastic flows corresponding to the PLC effect. The type of instabilities for natural aging until 8 hours is type B. For aging times longer than 12 hours, the amplitude of seriation strongly decreases and PLC effect is no longer observed. The onset deformation value for serrated flow increases with aging time. No PLC effect is observed for ageing treatment at 35, 50 and 70°C regardless of the duration of the treatment. Calculations of $\Delta\sigma_D$ and Δt_R for the W state and for natural aging treatment at times below 8 hours confirm the observations of type B PLC effect.
3. The observations of very energetic acoustic emission at the time of serrated flow confirm the presence of PLC effect in W state and after 5 hours of natural aging. In W state, a peak of AE is observed at yield stress that disappears for the others aging conditions. After an aging treatment at RT for more than 5 hours or at 50 and 70°C, the emission counts due to PLC effect disappear due to precipitation process. In W state and after natural aging for 5 hours, the noise recording shows a high level that could be associated to plastic deformation due to the PLC effect. In W state, the time analysis of the acoustic activity highlights the existence of three major stages: stage I corresponding to the yield stress, stage II to the plastic deformation, and stage III to the PLC effect. After natural aging for 5 hours, only stages II and III are observed; after aging at 50°C during 24h, only stage II is present.
4. A continuous increase in electrical resistivity with time during tensile test is observed due to the increase in defects number inside the material. Fluctuations can be observed for the W state sample.

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