On the Portevin-Le Chatelier instabilities in the industrial Al-2.5%Mg alloy

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Abstract:
The jerky flow or the Portevin–Le Chatelier effect is studied in the industrial Al-2.5%Mg alloy at imposed strain rate and at room temperature. Tensile tests, performed in the strain rate range $10^{-6}-10^{-1}$ s$^{-1}$, allowed to determine the range of instability and to study PLC characteristics as a function of strain and strain rate. We show that the reduction of the strain rate sensitivity of the flow strain is accompanied by a ductility reduction in the jerky flow domain. The obtained results are discussed in accordance with dynamic strain aging mechanisms.

Keywords: Portevin-Le Chatelier effect, Localized strain, Dynamic Strain Aging, Ductility.

1 Introduction
The instable plastic flow constitutes a major inconvenient during the formability of metallic materials. The Portevin-Le Chatelier (PLC) is one of these plastic heterogeneities [1-4]. It leads to heterogeneous mechanical properties, reduces the ductility of the deformed material and creates areas very sensitive to the corrosion. The strain localization zones are characterized by a dilating behavior which can cause the material rupture and, consequently, the failure of structures [1,2]. The optimization of the homogeneous material formability is based mainly on the results of characterization and modelling of the unstable plastic flow. PLC instabilities are observed in different materials with different histories and in different conditions. In Al–Mg alloys, which provide a large variety of applications due to their low weight and high mechanical strength, jerky flow appears around room temperature in a limited range of strain and strain rate [1-3]. The PLC effect is characterized by a macroscopic spatio-temporal localization of plastic flow. It appears in the form of a repeated stress drops in the stress-strain curve at imposed strain rate. The produced strain localizations on the sample surface (PLC bands) are static at low strain rates (Type C). They move by jumps at intermediate strain rates (Type B) and propagate at elevated applied strain rates (Type A). Initiation of plastic flow is generally preceded by a certain critical plastic strain $\varepsilon_c$ which is strongly dependent on the temperature and on the applied strain rate [1-3].

The microscopic origin of the PLC effect is associated to the dynamic strain aging (DSA) phenomenon resulting from the interaction between mobile dislocations and the clouds of impurities [1,4,5]. The solute atoms diffuse towards dislocations during their temporary arrests at local obstacles and increases, consequently, the plastic flow stress. The repeated breakaway of dislocations from the solute clouds reduces the strain rate sensitivity (SRS) of the flow stress which becomes negative. Therefore, the strain localizes
into narrow deformation bands and gives rise to serrated stress-strain curve at constant applied strain rate. The purpose of the present work is focused on the analysis of the temporal aspects of the PLC effect in the Al-2.5%Mg alloy at room temperature. We are interested to the determination of the domain of appearance of PLC plastic instabilities and to the study of the influence of the strain and the strain rate on the characteristic parameters of the unstable plastic flow.

2 Experimental

The material used in the present study is an industrial Al-2.5%Mg alloy. Its chemical composition in weight percent is given in TAB. 1. Polycrystalline flat samples (gauge length 42 mm, width 6 mm, thickness 2.25 mm) were machined in the rolling direction and deformed in tension at room temperature with a hard testing machine (i.e., constant driving velocity) at strain rates in the range $10^{-6} – 10^{-2}$ s$^{-1}$. Due to DSA, the plastic flow is unstable in these conditions. The samples are heat treated in air for recovery after rolling (at 400 $^\circ$C for 2 h) and quenched in water.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Mg</th>
<th>Cr</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-2.5%Mg</td>
<td>2.52</td>
<td>0.23</td>
<td>0.888</td>
<td>0.348</td>
<td>0.018</td>
<td>0.103</td>
<td>0.005</td>
</tr>
</tbody>
</table>

TAB. 1 – Chemical composition of the Al-2%Mg alloy (in wt.%).

3 Results and discussion

In the strain rate domain $10^{-6} – 10^{-2}$ s$^{-1}$ and at room temperature, the plastic flow becomes unstable beyond a certain critical plastic strain $\varepsilon_c$ and remains such until failure by necking of the sample. The SRS of the flow stress was found to be negative in the Al–2.5%Mg alloy. For a given strain, the flow stress level decreases with increasing strain rate.

3.1 Deformation curves and PLC instability types

FIG.1 shows the serrated stress-strain curves in the Al-2.5% Mg alloy obtained at room temperature for different imposed strain rates. Stress drops originate from strain localizations into narrow deformation bands inclined with respect to the tensile axis. Each localization results from the testing machine discharge, as the sample deforms with a local strain rate higher than the imposed one. The shape of the PLC instabilities depends strongly on the imposed strain rate (FIG.1). Three types of instabilities are observed.

At high strain rates (FIG.1-a et FIG.1-b), instabilities are of Type A. They are in the form of stress drops, corresponding to bands nucleation, separated by weak undulations due to their continuous displacements. Type A Bands generally initiate at the end of the sample and propagate continuously until the opposite one [2]. At intermediate strain rates, the stress drops are abrupt and are characterized by elastic reloading between tow successive drops (instabilities called of Type B). They are usually structured in stages separated by large drops, as shown in the insert of FIG.1-c. Every high stress drop corresponds to the PLC band appearance which moves by successive jumps producing additional stress drops of lower magnitude. Thus, each PLC band initiates after the other giving rise to an apparent displacement (correlated hopping band). At very low strain rates, instabilities are characterized by very large amplitudes and, partially, by a plastic reloading between two successive drops (FIG.1-d). These instabilities are called of Type C. The associated strains localizations occur randomly on the deformed sample.

The magnitude of the stress drops is one of the most conspicuous characteristics of the PLC instabilities. It is highly linked to the importance of DSA and then it reveals the heterogeneity grade of plastic flow [1,2]. The deformation becomes more heterogeneous as the magnitude of the stress drops is important. Indeed, for an imposed strain rate, the obstacles density (forest dislocations) increases when the strain increases and, therefore, the average waiting time of mobile dislocations increases. Thus, the time available to solute atoms diffusion is enhanced and, therefore, the DSA becomes more and more significant and the magnitude of the stress drops increasingly large. When the applied strain rate increases, at a given strain, the waiting time decreases and the DSA becomes less significant producing low stress drops in the stress-strain curve.
3.2 Strain rate sensitivity of the flow stress

A tensile test of strain rate jumps allowed showing the negative value of the SRS of the flow stress. FIG.2 shows the obtained curve and the temporal aspects of Types A and B instabilities, respectively, at strain rates of $10^{-3}$ and $10^{-4}$ s$^{-1}$. The change of applied strain rate is performed at strain $\epsilon=0.088$ (indicated by a dashed line in FIG.2).

The average SRS of the flow stress $\sigma$, at strain $\epsilon$, is given by the expression:

$$S = \frac{\Delta \sigma}{\Delta \ln \dot{\varepsilon}} \epsilon$$  \hspace{1cm} (1)
Where $\dot{\varepsilon}$ is the applied strain rate. $\Delta \sigma$ is the difference on the stress level produced when the strain rate changes from $10^{-3} \text{s}^{-1}$ to $10^{-4} \text{s}^{-1}$ (see the insert of FIG.2). Thus, $S$ is estimated to -3.04 MPa at strain $\varepsilon=0.088$.

The determination of $S$ at different strains shows that the sensitivity decreases with straining. This indicates that DSA is favoured by hardening. Indeed, the increase of dislocations densities during straining extends the waiting time of mobiles dislocations at local obstacles and, consequently, the DSA becomes more and more effective. As a macroscopic result, the magnitude of the stress drops increases during deformation (FIG.1) and transitions between instability types can occur, from Type A to Type B at $2 \times 10^{-3} \text{s}^{-1}$ and from Type B to Type C at $2 \times 10^{-5} \text{s}^{-1}$ for example.

3.3 Domain of PLC instability

PLC instabilities appear usually on the stress-strain curve beyond a certain critical strain $\varepsilon_c$ which depends on the imposed strain rate. $\varepsilon_c$ is a characteristic of the material and deformation conditions. It corresponds to the transition "positive sensitivity-negative sensitivity" of the SRS [1,5]. FIG.3 shows the variation of the critical plastic strain $\varepsilon_c$ and of the plastic strain at failure $\varepsilon_r$ when the imposed strain rate increases in the Al-2.5%Mg alloy at room temperature.

![FIG. 3 – PLC instability Domain of the Al-2.5%Mg alloy at room temperature. Effect of the imposed strain rate on the critical plastic strain $\varepsilon_c$ and the plastic strain at failure $\varepsilon_r$.](image)

$\varepsilon_c$ presents a normal behavior at high strain rates, where it increases when the applied strain rate increases, and an inverse behavior at low strain rates where it decreases with strain rate. The minimum of the curve $\varepsilon_c = f(\dot{\varepsilon})$, which corresponds to the transition "inverse behavior–normal behavior", coincides with the coexistence of both Type A and Type B instabilities on the stress-strain curve at a strain rate of $2 \times 10^{-3} \text{s}^{-1}$.

The normal behavior of the critical strain is explained by DSA models [4,5]. It is related to the vacancy generation and dislocations multiplication during plastic deformation. On the other hand, the inverse behavior is still the subject of controversies of many models [6-8]. The combined action of DSA and the presence of sheared precipitates by dislocations can be the cause of this behavior.

The strain rate dependency of the plastic strain at failure $\varepsilon_r$ (FIG.3) shows a ductility reduction of the Al-2.5% Mg alloy at room temperature. In fact, $\varepsilon_r$ decreases then increases when the applied strain rate increases. The ductility reduction is a consequence of the SRS reduction in the strain rate PLC domain.

4 Conclusion

The temporal aspects of the Portevin-Le Chatelier (PLC) effect has been studied extensively in the Al-2.5% Mg alloy at room temperature. The study shows that, for a given strain, instability shifts from Type C to
Type B then to Type A when the applied strain rate is increased. The necessary critical plastic strain for the onset of PLC instabilities manifests a normal behavior at high strain rates, where instabilities are of Type A, and an inverse behavior at low strain rates, where the instabilities are of Type B or Type C. The strain rate dependency of the plastic strain at failure shows a ductility reduction of the Al-2.5% Mg alloy in the strain rate PLC domain at room temperature.

References