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Experimental study by pyrometry of Portevin–Le Châtelier plastic instabilities—Type A to type B transition

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The dynamic strain aging phenomenon which occurs in some materials under certain temperature and strain rate conditions can cause a localization of the plastic strain in the form of Portevin–Le Châtelier (PLC) bands. According to the strain rate and the temperature, the spatiotemporal pattern of these bands changes and three main types of band are identifiable (types A–C). The increment of plastic strain associated with each band causes an increment in temperature which can be measured by infrared pyrometry. This experimental technique was used in this paper to study the PLC phenomenon in an aluminium–copper alloy at ambient temperature and to visualize the strain localization patterns. Some characteristics of these bands are measured: bandwidth, slope angle, increment of plastic strain in the band, time between two band formations, time of band formation, propagation velocity of the bands, band spacing. . . The evolution of these characteristics according to the strain enables us to suggest an explanation of the type A–type B transition.

Keywords: Dynamic strain aging; Portevin–Le Châtelier bands; Plastic strain localization; Infrared pyrometry

1. Introduction

In general, at the macroscopic scale, the plastic strain in materials is homogeneous. However, under certain temperature and strain rate conditions, it can become heterogeneous. There is then localization of the plastic strain. The phenomena of static and dynamic strain aging can be the origin of this heterogeneity of the plastic strain. In the case of the dynamic strain aging (DSA) phenomenon, the localization of the strain is characterized in a tensile test by the formation and the propagation along the sample of plastic strain bands of few millimeters of width and tilted of around 60° with the tensile axis. These bands have been discovered in 1909 in the mild steels by André Le Châtelier [1] and in 1923 by Albert Portevin and François Le Châtelier in aluminium–copper alloys [2] and are called bands of Portevin–Le Chatelier (PLC). In a tensile test at fixed strain rate, these bands are associated on the tensile curve with repeated

serrations resulting from a succession of stress drops. In the case of test at fixed stress rate, the PLC bands are characterized by discontinuities in the form of strain stages. This localization of the plastic strain can appear in materials with different crystal lattice (mild steels, austenitic stainless steels, aluminium alloys, zirconium alloys. . .).

At the microscopic scale, this phenomenon is explained by the dynamic interaction of mobile dislocations with the solute atoms in insertion or substitution. The first physical mechanisms proposed by Cottrell [3] and Friedel [4] were based on a viscous dragging of the solute atoms by dislocations. Then later, Mac Cormick [5] and Van den Beukel [6] showed that the slip of dislocations is not continuous, but discontinuous. Dislocations are temporarily stopped on the obstacles (forest, precipitates. . .) during a waiting time t_w . During this waiting time, the diffusion of the solute atoms creates an additional anchoring of dislocations. Controversies persist on the exact diffusion mechanisms of the solute atoms. The bibliography on dynamic strain aging is abundant and syntheses were periodically written [7–13].

When a tensile test is performed at imposed strain rate, the macroscopic aspect of the heterogeneities of strain during PLC phenomenon is associated with serrations on the stress strain curve and can be classified in three types depending on

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the spatiotemporal appearance of these bands ([8,9,14–18]). The type C corresponds to the chaotic formation of the bands (discontinuous and not correlated). Each stress drop on the tensile curve corresponds to the formation of one band. The type B corresponds to the discontinuous but regular formation of the bands (each new band is created just near the previous band and so on). Each created band is characterized by a stress drop on the stress strain curve too. Type A bands correspond to a continuous propagation of a band along the specimen. With each type of band (A, B or C) is associated a type of serration on the stress strain curve, more or less easily identifiable. The occurrence of these different types of bands which correspond to various spatiotemporal types of localization depends on external parameters (level of strain, strain rate, temperature, stiffness of the tensile machine, geometry and surface quality of the samples) and internal parameters (alloy composition, crystal lattice, standard structure and solute atoms type and content, density of mobile dislocations, type of obstacles, grain size). The influence of the external parameters (strain rate and temperature) was studied the most. When the strain rate increases (the waiting time of dislocations decreases) or the temperature decreases (mobility of the diffusing species decreases) the localization of the bands evolves from the type C to the type B, then type A. Today, the transitions between these various types of bands are not still clearly explained.

In general, the appearance of the serrations on the tensile curve appears only after a certain amount of strain ε_c ([19–22]). Some characteristic quantities are associated with each type of band (which depend on the external and internal parameters): bandwidth (types C and B), slope angle, time between two band formations, time of band formation, propagation velocity (in the case of the types B and A), increment of plastic strain. . .

In order to study the spatiotemporal evolution of PLC bands, various authors used the optical extensometry technique. This technique allows to measure the strain along a tensile specimen. This test consists in a one-dimensional measurement device whose frequencies vary between 50 Hz (Ziegenbein et al. in 2000 [21], Casarotto et al. in 2003 [23] and Klose et al. in 2003 [24]) and 250 Hz (Casarotto et al. in 2005 [25]). The spatial resolution of these devices is related to the size of the patterns drawn on the specimen. Typically, the resolution is about 1 mm, which remains high compared to the width of PLC bands. The strain resolution is about 0.05%. In order to obtain two-dimensional measurements and thus to evaluate, for example, the slope angle of the bands and their width, various measurement techniques were developed: in 2004, Shabadi et al. [26] used a technique of speckle interferometry to study the initiation of PLC bands. In 2005, Jiang et al. [27] used a technique of digital image correlation from a speckle pattern in order to obtain the strain field. The acquisition frequency of these different devices is about few tens of Hertz. In 2005, Tong et al. [28] used an ultra high speed camera with an acquisition frequency of 5 kHz and a technique of digital image correlation to determine the strain field during the formation of a PLC band. This technique allows to precisely visualize the band formation. More recently, Ait-Amokhtar et al. [29] used the same technique with an acquisition frequency

of 9 Hz to study the nucleation and the propagation of type A, B and C PLC bands in an Al4.5%Mg alloy. Recently, various authors have developed the infrared thermography technique in order to study PLC bands [30]. Indeed the plastic strain is accompanied by a dissipation of the mechanical work in heat, which generally causes an increase in the temperature. This technique seems very promising because it enables to have a high acquisition frequency (about 400 Hz in [31]) and even to quantify the plastic strain in the band with a good accuracy [30]. The pyrometry technique allows to measure both characteristic times and distances of PLC bands.

The objective of this paper is to study the influence of the strain and the strain rate on PLC bands with infrared pyrometry technique. Within this framework we were interested in an aluminium–copper alloy which enables us to have the PLC bands at ambient temperature. In a first part we will describe the experimental device and the analysis method used in this study. In a second part, we will present the results obtained for the type A, type B and type C bands. Then we will detail the evolution of the bands parameters according to strain and strain rate and we will more particularly discuss on the type A–type B transition.

2. Experimental device and analysis method

2.1. Material

The material used in this study is an aluminium–copper alloy (4% copper) heated at 500 °C during 30 min and then water quenched. Immediately after quench, the copper concentration content in substitutional solid solution is high and this alloy is sensitive to DSA in a temperature range around 20 °C.

2.2. Device of loading and characteristics of the tests

Immediately after quench, tensile tests were carried out on a screw testing machine, at the ambient temperature (20 °C), with a constant strain rate, ranging between $2.38 \times 10^{-4} \text{ s}^{-1}$ and $2.14 \times 10^{-2} \text{ s}^{-1}$. Prismatic specimens of 12 mm wide, 3 mm thickness and 60 mm length were machined. The specimen's surface was in the as-rolled condition. In order to study the influence the strain rate on PLC phenomenon, four tests were carried out at various imposed strain rate (Table 1). The tensile stress is measured with a force sensor (force accuracy: $\pm 0.5\%$; frequency: 1000 Hz) and the nominal tensile strain is deduced from the measurement of the grips displacements.

Table 1
Tests carried out

Test	Sampling frequency (Hz)	Type of bands observed	Strain rate (s^{-1})
(1)	25 and 500	Type C	2.38×10^{-4}
(2)	320	Type A and type B	4.76×10^{-3}
(3)	320	Type A and type B	1.19×10^{-2}
(4)	320	Type A and type B	2.14×10^{-2}

2.3. Temperature measurement

The measurement of the temperature field on the specimen surface is carried out with a pyrometry technique. We thus use an infrared camera whose spectral range is between $3.9\ \mu\text{m}$ and $4.5\ \mu\text{m}$. The power radiated by the surface of the specimen is collected by 50 mm focal length objective which focus the image on the matrix of the CCD camera. The camera is fixed and records moving material points on the specimen. The spatial resolution is of $0.3\ \text{mm}$ by pixel. An aperture time of the camera of $1500\ \mu\text{s}$ allows to detect temperatures ranging between $5\ ^\circ\text{C}$ and $50\ ^\circ\text{C}$. The noise of the camera is around $20\ \text{mK}$. Except in the case of test 1, the sampling frequency of the camera is of $320\ \text{Hz}$, i.e. a period of $3.125\ \text{ms}$. The sampling frequency during test (1) is $25\ \text{Hz}$ in order to reduce the data storage during the long tests. The pyrometer is calibrated on a black body in order to obtain the relation between the signal delivered by the camera and the temperature of the observed surface. In order to eliminate the effect of the emissivity of the surface on the determination of the temperature, the specimens are covered with a fine coat of black paint.

3. Results and discussion

3.1. Macroscopic appearance of dynamic strain ageing

3.1.1. Observation of the type B bands

For the tests (2), (3) and (4), we can notice the presence of type B PLC bands. On the stress strain curve (Fig. 1), they are first characterized by regular small serrations (a) of increasing amplitude during the test and second by more significant serrations (b). Each small serration corresponds to the formation of one PLC band and the stronger serrations correspond to the formation of several PLC bands at the extremity of the specimen. This aspect was detailed in a previous study [30].

Fig. 2 shows the temporal evolution of the temperature in the center of two consecutive bands. We can notice an increase in

Fig. 1. Stress strain curve for the test (3) at the strain rate of $1.19 \times 10^{-2}\ \text{s}^{-1}$.

Fig. 2. Temperature evolution in the center of two consecutive bands during test (3) (strain rate: $1.19 \times 10^{-2}\ \text{s}^{-1}$).

the temperature which corresponds to the plastic strain during each band formation. In the case of this test, for a nominal strain of 15.8%, the temperature increment during the formation of the first band ($t = 13.2875\ \text{s}$) is $0.74\ ^\circ\text{C}$. This curve allows us to define the time of band formation and the time between two consecutive bands noted respectively t_f and t_{mb} . The time of band formation is defined as the time corresponding to the temperature increase from 5% to 95% of the total temperature increment in the band (see Fig. 2). In the case of the test (3), for a nominal strain of 15.8%, the time of band formation can be estimated at $7.8 \pm 1.6\ \text{ms}$ for the first band and $6.3 \pm 1.6\ \text{ms}$ for the second. Fig. 2 also allows to define the time between two consecutive band formations. We suppose that the moment of band formation is the time when the increase in temperature in the band reaches 50% of the total temperature increment. In the case of Fig. 2, time between two band formations is about $51.7 \pm 1.6\ \text{ms}$ for a nominal strain of 15.8%.

Fig. 3a shows the fields of temperature increment on the specimen surface corresponding respectively to the two band formations presented in Fig. 2 recorded for time $t = 13.2875\ \text{s}$ and $t = 13.3406\ \text{s}$. These two cartographies of the temperature increment show that the increase in temperature and thus the plastic deformation are localised in a band across the width of the specimen. The slope angle between the band direction and the specimen traction axis is of $61 \pm 1^\circ$. Fig. 3b represents the profile of the temperature increment along the specimen axis (x axis) which corresponds to the first and the second bands represented in Fig. 3a. The temperature increment is taken for the first and the second bands respectively between the points A and B and the points A' and B' plotted in Fig. 2. These two profiles enable us to define the bandwidth along the traction axis noted d and the distance between two consecutive bands along the traction axis noted δ and called band spacing. In the case of the test (3), and for a nominal plastic deformation of 15.81%, the bandwidth and the band spacing along the traction axis are respectively equal to $2.9 \pm 0.15\ \text{mm}$ and $1.4 \pm 0.15\ \text{mm}$. The uncertainty on the bandwidth and on the band spacing is

Fig. 3. Observation of two consecutive bands during test (3) at the strain rate of $1.19 \times 10^{-2} \text{ s}^{-1}$ (a) fields of temperature increment on the specimen surface recorded for times $t = 13.2875 \text{ s}$ and $t = 13.3406 \text{ s}$ (b) profile of the temperature increment along the specimen axis.

related to the pixel size of the camera. A calculation similar to that presented in [30] shows in our case that a sampling frequency of 320 Hz enables us to strongly limit the error on the bandwidth due to the heat diffusion. This error can be estimated at approximately 0.05 mm that is lower than the size of a pixel (0.3 mm). By taking into account the slope angle of the band with the traction axis, we can also determine the bandwidth and the band spacing along an axis perpendicular to the direction of the band. Then we obtain respectively a bandwidth of 2.6 mm and a band spacing of 1.2 mm.

Fig. 4 represents the position of the initiated bands along the specimen axis. The position is normalized by the length of the sample. In order to eliminate the edge effects, only the bands sufficiently far away from the edges (i.e. formed between 10% and 90% of the specimen length) are plotted. The two consecutive bands plotted in Fig. 2 are marked in Fig. 4. The distance between these two bands (1.4 mm) and the time between these two band formations (51.7 ms) are respectively higher than the spatial (0.3 mm) and the temporal resolution (3.1 ms) of our experimental device. The same remark can be made for all the type B bands plotted in Fig. 4. So, we can conclude that there is a discontinuous propagation of these bands along the length of the specimen. In Fig. 4 we can notice that the formation of the bands is done in a well-ordered way. At the end of the test (i.e. for nominal deformations higher than 17%), we can note a slight disorganization of these bands which are located towards the necking zone.

One can then define the apparent propagation velocity as the ratio between the band spacing and the time between the two band formations:

$$V_{\text{app}} = \frac{\delta}{t_{\text{mb}}} \quad (1)$$

Considering the two consecutive bands presented in Fig. 2, for a nominal strain of 15.8% and a strain rate of $1.19 \times 10^{-2} \text{ s}^{-1}$,

Fig. 4. Band position along the specimen axis, according to the nominal strain, during test (3) at $1.19 \times 10^{-2} \text{ s}^{-1}$.

Fig. 5. Test (2) at a nominal strain $\varepsilon = 3.88\%$ (strain rate: $4.76 \times 10^{-3} \text{ s}^{-1}$): (a) temperature evolution in the center (point J) of the specimen during the type A band propagation and (b) fields of temperature increment, measured at three characteristics times.

we measure $\delta = 1.4 \text{ mm}$ and $t_{mb} = 51.7 \text{ ms}$. We thus obtain an apparent propagation velocity V_{app} of 27 mm/s .

3.1.2. Observation of type A bands

For the tests (2), (3), (4) and for weak nominal strain, it becomes impossible to distinguish two consecutive band formations. The more the strain rate increases, the more the transition from bands of the type A towards bands of the type B occurs for high nominal strain. However it is very difficult to precisely quantify a critical nominal strain for the transition in experiments. Indeed, there is a transition range where type A and type B bands appears at the same time. For weak nominal strain, the discontinuous propagation of type B bands gives way to a continuous propagation of a plastic strain front (type A band). Then, it is impossible to determine a time between two band formations and a band spacing. Fig. 5a shows the temperature evolution versus time in a point J located at the center of the specimen. We measure a sudden increase in the temperature when the plastic strain front crosses the point J. For the test (2) at a nominal deformation of 3.88% (Fig. 5a), the temperature increment is estimated at 0.18°C . Fig. 5b shows three fields of temperature variations when the band crosses on the measurement points I, J and K defined in Fig. 5a. The increment of temperature is calculated with the initial temperature field at the time $t_0 = 7.409 \text{ s}$ corresponding to the beginning of the band propagation on the right-hand side of the specimen. From these three fields, we can determine the slope angle of the propagation front with the axis of the specimen and measure the propagation velocity of this plastic strain front. In the case of the test (2) and for a nominal strain of 3.88% we find an angle of $63 \pm 1^\circ$ and a propagation velocity of 49.5 mm s^{-1} between the points

K and J and 48.6 mm s^{-1} between the points J and I. The slope angle with the specimen axis is thus of the same order as the one measured in the type B bands.

3.1.3. Observation of type C bands

For lower strain rate (for example for the test (1), $2.38 \times 10^{-4} \text{ s}^{-1}$), the stress strain curve does not present (Fig. 6) any more significant serrations corresponding to the formation of bands on the edges of the specimen as in the case of type B. Regular stress jumps are then observed whose amplitude is more significant than in the case of type B bands and increases during the test. These serrations are always associated with the

Fig. 6. Stress strain curve for the test (1), at the strain rate of $2.36 \times 10^{-4} \text{ s}^{-1}$.

Fig. 7. Band position along the specimen axis, according to the nominal strain, during test (1) at $2.38 \times 10^{-4} \text{ s}^{-1}$.

formation of PLC bands but these ones are formed in a random way along the specimen (type C bands). Fig. 7 represents the normalized position of the bands along the sample. However, we can notice that at the end of the test, we have a slight organization of these bands. For a nominal strain of 13.7%, we can measure a time between two bands of 3.7 s and a slope angle of the band with the specimen axis of $58 \pm 1^\circ$. In order to measure with sufficient precision the duration of band formation, we carried out a thermal recording at a frequency of 500 Hz. Then, for a nominal strain of 13.7% and a strain rate of $2.38 \times 10^{-4} \text{ s}^{-1}$, we find a duration of band formation of 3.7 ms. In the band, the temperature increment is of 1.04°C and the bandwidth is of $3.7 \pm 0.15 \text{ mm}$.

3.2. Evolution of the characteristics of the bands according to the nominal strain and the strain rate

Taking into account the precision of our experimental device, we did not measure significant variation of the slope angle of the bands. However, we highlighted a slight decrease in the bandwidth with an increase of the strain rate. Thus, we were more particularly interested on the time between two band formations (case of type B and type C), the band spacing (type B), the apparent propagation velocity (type A and type B) and the increment of plastic deformation in a band (type A, type B and type C).

3.2.1. Time between two band formations

Fig. 8 shows the evolution of the time between two band formations according to the nominal strain, for four strain rates, when this quantity is measurable. It is noted that time between two band formations increases with the nominal strain and decreases when the strain rate increases. In Fig. 8, we can show that the evolution of the time between two band formations with the nominal strain can be approximated by a linear law in a log-log diagram. Thus, we can write a relation between t_{mb} and

Fig. 8. Evolution of the time between two band formations according to the nominal strain, during tests (1) to (4).

the nominal strain ϵ :

$$t_{mb} = D\epsilon^E. \quad (2)$$

For test (3) (strain rate of $1.19 \times 10^{-2} \text{ s}^{-1}$)

$$D = 0.15 \quad \text{and} \quad E = 0.6068. \quad (3)$$

The standard deviation between the experimental results and the regression is 0.07 s. The increase of the time between two band formations with the nominal strain was already noted by Jiang et al. [27] in an Al4%Cu alloy. More recently, Ait-Amokhtar et al. [32] also showed in experiments that this time between two bands (called reloading time) increases when the nominal strain increases and when the strain rate decreases. This effect can be explained by the fact that the waiting time of mobile dislocations on glide obstacles and thus the time between two band formations increase with the strain. Indeed, according to the Orowan' law, we can express the waiting time t_w according to the strain rate and the elementary plastic strain noted Ω which corresponds to the strain obtained when all mobile dislocations accomplish a successful activation event: $t_w = \Omega/\dot{\epsilon}$ [33]. It can be shown in experiments that we can consider that the elementary plastic strain increases linearly with the strain [34]. An increase in the nominal strain thus results in an increase in the waiting time and an increase in the time between two band formations. The relation can explain the increase in the waiting time and therefore in the time between two band formations when the strain rate decreases, which is noted in our experiments in Fig. 8.

3.2.2. Band spacing

Fig. 9 represents the evolution of the band spacing along the axis of the specimen according to the nominal strain for the various tests except in the case of type A bands (beginning of the test (2), (3) and (4)) where the band spacing cannot be defined. We can note an important dispersion of the band spacing in Fig. 9 because this band spacing is rather weak compared with the spa-

Fig. 9. Evolution of the band spacing according to the nominal strain, during tests (2), (3) and (4).

tial resolution of our device. However, this figure shows a slight reduction in the band spacing when the plastic strain increase. Very few results in literature give the evolution of this distance during a test. However, we can notice that Casarotto et al. in 2003 [23] measured the evolution of this band spacing during a test in a Cu15%Al alloy. They also highlighted a reduction in this distance with the strain too. Fig. 9 also shows that the strain rate has only very low influence on this band spacing. Kang et al. [35] highlighted in experiments a small increase in this band spacing but in an Al Mg alloy.

3.2.3. Apparent propagation velocity

Fig. 10 represents the apparent propagation velocity according to the nominal strain. As the distance between two bands decreases when the strain increases and the time between two band formations increases when the strain increases, a decreasing apparent speed is well noted when the strain increases. An

Fig. 10. Evolution of the band propagation velocity according to the nominal strain, during tests (2), (3) and (4).

increase in the apparent propagation velocity with the strain rate of the test can also be highlighted. In Fig. 10, if we put the values of propagation velocities of the plastic strain front in the case of the bands of type A, we can observe a continuity between this front velocity and the apparent propagation velocity of the type B bands.

3.2.4. Temperature increment and plastic strain increment in the bands

For a nominal strain of 15%, the temperature increment is 0.74 °C and 1.1 °C, respectively for tests (3) and test (1). For the same nominal strain, the stress for each test can be quantified from the stress strain curve: 325 MPa for test (1) and 295 MPa for test (3). These values allow to deduce the axial plastic strain increments in the bands noted $\Delta\epsilon^p$ from the heat transfer equation in the adiabatic case [30]:

$$\Delta\epsilon^p = \frac{\rho C \Delta T}{\beta \sigma} \quad (4)$$

with $\rho = 2800 \text{ kg m}^{-3}$ the density, $C = 900 \text{ J kg}^{-1} \text{ K}^{-1}$ the specific heat, ΔT the temperature increment, $\beta = 0.9$ the Taylor Quinney coefficient which represents the plastic power converted into heat and σ the axial tensile stress.

The adiabatic hypothesis introduces an error on the plastic strain increment in the band. Eq. (4) allows to estimate a lower bound of the plastic strain increment. This error which depends on the sampling frequency can be estimate with the calculation made in [30]. For the sampling frequency of 25 Hz, 320 Hz and 500 Hz, we find respectively an error of 58%, 4.5% and 1.2% on the temperature increment and also on the strain increment.

If we suppose that the stress is almost constant during the band formation, for a nominal deformation of 13.7%, we find strain increments of $0.615 \pm 0.015\%$ and $1.05 \pm 0.01\%$ respectively for the tests (3) and (1) (with the sampling frequency of 500 Hz). Fig. 11 gives the evolution of the temperature increment according to the nominal strain in the case of the test (1)

Fig. 11. Temperature increment in the band according nominal strain, during tests (1) and (3).

Fig. 12. Evolution of the time of band formation according to nominal strain, during test (3).

and the test (3). This figure highlights an increase in the temperature increment in the band and thus in the increment of plastic strain when the strain increases. There is an important dispersion of the strain increments in the band during the test (1). That can be explained by a weak sampling frequency (25 Hz).

3.3. Type A–type B transition

During test (3) (strain rate of $1.19 \times 10^{-2} \text{ s}^{-1}$) a transition from type A bands towards type B bands was noticed when the nominal strain increases. The value of the nominal strain when the transition occurs is difficult to evaluate because in a strain range around this transition we show at the same time bands of type A and bands of type B. It is also easier to define the strain range of the transition. During test (3), we can estimate this transition strain range between 5% and 6%.

In order to explain this transition from type A to type B, we compared the time of band formation t_f and the time between two-band formations t_{mb} . Fig. 12 shows the evolution of the time of band formation according to the nominal strain, for test (3), in the case of the type B bands (strain rate of $1.19 \times 10^{-2} \text{ s}^{-1}$). The curve in Fig. 12 underlines a reduction in the time of band formation with the strain: in a log–log diagram (Fig. 12), this evolution can be considered as linear. Thanks to a linear regression we obtain a power law evolution of the time of band formation according to the strain:

$$t_f = F\varepsilon^G. \quad (5)$$

In the case of the test (3), one obtains

$$F = 0.0008 \text{ s} \quad \text{and} \quad G = -1.0925. \quad (6)$$

In the case of type B bands (for example for a nominal strain of 10% during the test (3)), the time of band formation and the time between two bands are respectively $9.9 \times 10^{-3} \text{ s}$ and $3.8 \times 10^{-2} \text{ s}$. The values found in this study are of the same order as those measured by Louche et al. [31] (the development time of the band was estimated at 10 ms in an Al–4 wt.%Mg alloy)

and by Tong et al. [28] (the development time of the band was estimated between 3 ms and 5 ms in an Al–2.5 wt.%Mg alloy). However no data are available in the literature concerning the evolution of this time of band formation according to the nominal strain.

During test (3), for a nominal strain of 10%, time between two band formations is $3.8 \times 10^{-2} \text{ s}$. We can notice that in the case of bands of type B, the time of band formation is much lower than the time between two bands. In this case, the formation of two consecutive bands is really distinct. Then, there is really a discontinuous propagation of the bands which is a characteristic of the bands of type B. Taking into account the reduction in the time of band formation and the increase of the time between two band formations, we can suppose that below a certain nominal strain, the time of band formation becomes higher or equal to the time between two band formations. We determined previously that in the case of test (3), the type A–type B transition took place between 5% and 6%. For a nominal strain of 5%, the relations (2) and (4), allow to determine a time of band formation of 0.021 s and a time between two band formations of 0.028 s for a strain rate of $1.19 \times 10^{-2} \text{ s}^{-1}$. We can remark that the time of band formation and the time between two band formations are of the same order for a nominal strain of 5% which corresponds to the type A–type B transition. This transition from type A towards type B can be also explained by a simultaneous increase in the time between two band formations and a decrease in the time of band formation. By extrapolation, the range of the bands of type A corresponds to a time of band formation higher than the time between two band formations. It explains the continuous character of the propagation of the type A bands.

4. Conclusion

In this paper, we studied the Portevin Chatelier bands of type A, B and C in a Aluminium Copper alloy using the temperature measurement technique of infrared thermography. We were more particularly interested in the study of the band characteristics such as the band spacing, the time of band formation, the time between two band formations, the bandwidth, the slope angle with the axis of the specimen and the temperature increment in the bands. We also studied the evolution of these various characteristics according to the nominal strain and the strain rate. In particular, we highlighted an increase in the time between two band formations and a reduction in the time of formation with an increase in the nominal strain. We noted that in the case of bands of type B corresponding to a discontinuous propagation, the time of band formation was lower than the time between two band formations. We also showed that the type A–type B transition from a continuous propagation towards a discontinuous propagation corresponded to the equality between the time of band formation and the time between two band formations.

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