Thermographic study of nucleation and propagation of Portevin-Le Châtelier bands

by H.-A. Crostack , R. Zielke, X. Feng , G. Fischer

Chair of Quality Management, University of Dortmund, Dortmund, Germany, D-44227

Abstract

A common technological method to increase the strength of pure metals is to introduce foreign atoms in metallic solid solutions in order to obstruct the dislocation motion. In some regimes of temperature and loading-rate, the interaction of such foreign atoms with dislocations can result in a negative strain-rate sensitivity, dynamic instability and deformation localization, leading to the nucleation and propagation of so-called Portevin-Le Châtelier (PLC) bands. From a technological point of view, the development of such bands results in a reduction of surface quality and ductility, and therefore is undesirable. From the appearance of the recorded load serration, three types of PLC bands have been commonly distinguished: type-A bands, which are nucleated near one specimen grip during a slight yield point, and then propagate continuously along the specimen with only slight load fluctuations; type-B bands, which are also nucleated near one grip, but propagate discontinuously along the specimen accompanied by rather regular load serration; and type-C bands, which are nucleated at random sites along the specimen length and cause strong regular load drops at rather high frequency. The unstable plastic flow is basically traced back to negative strain-rate sensitivity (SRS) of the flow stress, namely a decrease of the flow stress with increasing applied strain-rate. Such an anomalous behaviour may be induced by the dynamic strain ageing (DSA) within certain ranges of loading rates and temperatures.

In this work, experimental results of a detailed investigation of the morphology and kinematics of PLC bands carried out by a high-speed infrared camera are presented. The material studied here is the technical AlMg3 alloy (Al-3.11wt%Mg-0.26wt%Si-0.22wt%Fe-0.18wt%Mn). This material was prepared by cold-rolling into 1.5 mm sheets. The tensile samples cut from the sheets with the tensile axis aligned with the rolling direction had a gauge length of 4 mm and a width of 2 mm (Fig.1). Most of them were ground and polished.

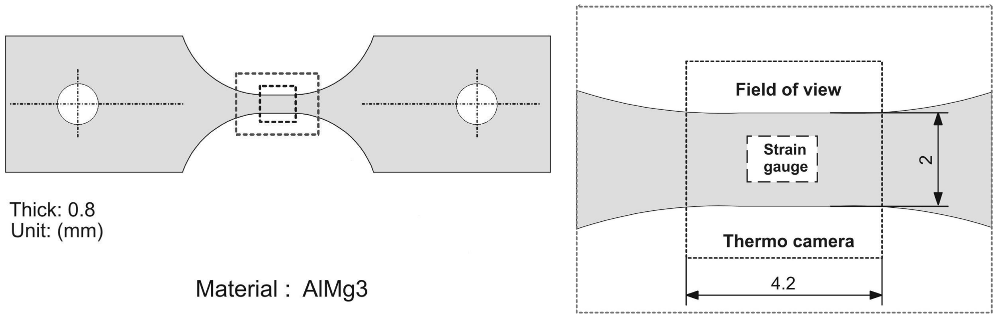

Fig. 1. Geometry of specimen and infrared camera field of view.

All samples were annealed in air at 673 K for 2 hours and quenched into water. Finally, strain gauges with active length of 1.5 or 3 mm were applied on their back side.

Uniaxial tensile tests were performed at room temperature using a miniaturized test rig. The applied strain rate ranges over more than two magnitudes of order (from $9.3\ 10^{-5}$ to $4.7\ 10^{-2}$ per second). During tensile loading thermal pictures of specimen gauge length were recorded using a high speed infrared camera. The infrared camera equipped with cadmium-mercury-telluride (CMT) detector has a maximum full frame rate of 885 Hz, a pixel resolution of 256 x 256 and temperature sensitivity of 12 mK in the spectral range from 3.4 to 5.1 µm wavelength (mid infrared domain). The selected magnification (2.5x) corresponds to a field of view of 4.2 x 4.2 mm^2 and a spatial resolution of 17.3 µm.

To detect and analyse PLC bands by infrared camera the feature of these bands to be a type of localized plastic deformation was used. Plastic deformation of metals is accompanied by a dissipation of mechanical energy into heat. This dissipation generally results in an increase in temperature. Thus, the bands are regions of elevated temperature. Due to slight temperature changes caused by plastic deformation and a certain inhomogeneity of IR emissivity (also in case of polished specimen surfaces) the PLC bands are visible in the temperature pictures, hardly. Therefore, the evaluation of temperature picture series aimed at the determination of temperature rate fields. To this end two methods were used.

In case of method 1 pairs of pictures taken at a fixed time difference are substracted pixel by pixel. The time difference has to be selected suitable. This method is relatively easy to apply and ensures the same lateral resolution as the thermal pictures. A drawback is that a relative deformation occurred between recording both pictures used for substraction are not taken into consideration.

Method 2 used an image correlation algorithm and calculates both temperature and strain rate fields. In this case, picture 1 of pair (reference) is divided in a regular matrix of overlapping subimages (facets) for each of which a tensor of average plane strain rate and average temperature rate is calculated, iteratively. The lateral resolution is lower than for method 1 because for calculating a value of strain rate and temperature rate some pixel of thermal picture are needed. As the image correlation algorithm based on grey value edges within the pictures the specimen surface is recommended not to polish. The fields of temperature rate and strain rate are used to demonstrate the effect of applied strain rate on nucleation, propagation and morphology of PLC bands, qualitatively.

To visualize the kinematics of PLC bands, a spatio-temporal representations of PLC banding is used. This representation is made by cutting narrow strips from temperature rate pictures aligned with the longitudinal direction in the middle of specimen (Fig. 2a). The intersection point of this strip and the band is assumed to represent its position at a given time. All such snapshots of the band (Fig.2b) are put together to form the trace of its motion (Fig. 2c). This trace is called the trajectory of a PLC band. Finally, the picture of band trajectories is overlaid by a stress-time and a strain-time curve. In this way, the positions of PLC bands can be shown in a picture simultaneously with the evolution of the strain and stress.

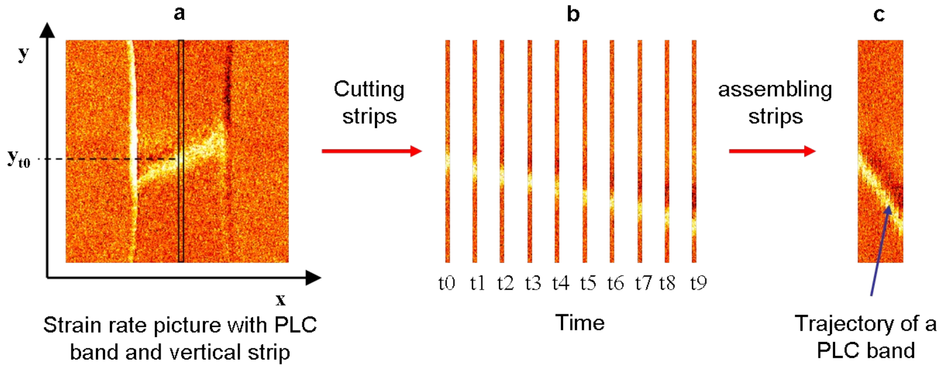

Fig. 2. To represent the position of a PLC band, a narrow strip in the middle of specimen is selected (a), multiple strips from consecutive moments (b) are put together to form the trajectory of a PLC band (c).

Using this representation method, the kinematics of PLC bands will be visualized. In the example given in Fig. 3, some PLC bands are nucleated at the top of picture (grip area of specimen) and propagate through this field in negative y-direction. The bands (bright lines) formed later are stronger than the previous ones, implying that the strain increment due to the band is increasing with strain.

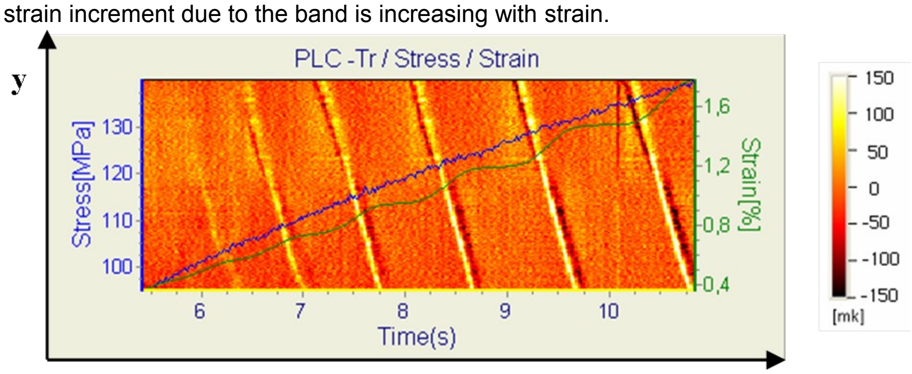

Fig. 3. Experimental results on the nucleation and propagation of type-A PLC bands at 2.7×10^{-3}/s (strain rate) correlated in time with stress (blue) and strain (green) results. A picture of the band trajectories (bright areas) is shown in the background.

In the strain-time curve (green) is visible that each band propagation period is accompanied by a steep strain increase whereas no stress drops are found in the stress-time curve (blue). That is typically for the first bands which are detected in a tensile experiment. The linear path of trajectories in Fig. 3 implies that the velocity of first bands is almost constant.

In the presentation will be shown, that the kinematics of PLC bands is changing with strain and dependent on applied strain rate. To quantify the kinematics of PLC bands band velocities were measured. The average velocity of the bands of a tensile experiment performed with constant applied strain rate was found to deminish as deformation proceeds. After a strong velocity reduction at the beginning, the curve seems to be approaching a saturation value. In order to show the band velocity dependency on strain rate the average velocities of the first 5 bands of each experiment were calculated. The results presented in the paper will show that this average band velocity increases with strain rate. A power law relation between both quantities could be fit to the experimental data (exponent of 0.72).

The measured temperature rate and strain rate fields as well as the band parameter (velocity, strain increment) will be used to verify additional FE simulations of PLC band nucleation and propagation.

Keywords: Portevin-Le Châtelier (PLC) effect ; Thermography; Infrared camera, Digital image correlation