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TRACKING THE PROPAGATION OF DEFORMATION BANDS BY MEANS OF AN OPTICAL SCANNING EXTENSOMETER

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Abstract – The Portevin-Le Châtelier effect has been investigated by means of an optical extensometer during tensile deformation of Al-3wt%Mg specimens. The propagation of bands with a concentrated deformation has been detected and its velocity measured. A real-time scanning of the phenomenon makes it possible to track the band propagation with an optical sensor.

Keywords PLC-bands, tensile testing, tracking

1. INTRODUCTION

The deformation working of metals can be subject to phenomena, related to material microstructure, which are undesirable since they reduce material workability and product quality. Orange-peel and Lüders bands, for instance, are some of the better known among such phenomena. The Portevin-Le Châtelier (PLC) effect is another known phenomenon which takes place during plastic deformation of ductile alloys under different working conditions. Characteristic of this effect are the so called PLC bands, regions of the material that, one after the other, are affected by instantaneous local deformations. The development of such deformations is connected to discontinuities in applied stress as general relaxations of stress are induced. The appearing of bands occurs often in an orderly succession, giving rise to a real propagation of deformation along the specimen.

The aim of our project is not just the investigation of materials behaviour, in order to find out the process parameters for which irregularities are suppressed, but also to reach a theoretical comprehension of the PLC effect. To achieve this comprehension we combine experimental work with numerical models. A comparison between simulation results and experimental data is carried out to evaluate the importance of physical principles in ruling the phenomenon. This paper deals with the experimental part of this research project.

With the developed measurement set-up it is possible to determine the dimensions and conditions typical of the phenomenon. Since the PLC effect is an intrinsically local phenomenon, usual material test methods don't characterize it completely as they provide us only with global information. Despite that, however, few investigations are focused on the description of the development of local bands. They are mainly based on clip-on extensometer [1,2], on laser extensometer [3] or on laser speckle interferometry [4]. A laser extensometer is already employed by our research group with interesting results [3]. It is applied to a tensile test machine and during a test it continuously surveys the local deformation states of many small regions of the specimen. The new optical extensometer, that at present is under development, is based on the same idea, but operates with a larger number of regions and a higher scanning frequency. The real-time processing of data about band propagation will soon make it possible to move a camera simultaneously with the band front, in order to record video sequences of the band development with a high resolution.

2. PORTEVIN-LE CHÂTELIER EFFECT

The Portevin-Le Châtelier effect is an instability phenomenon that afflicts ductile alloys during plastic deformation. It can be characterized by a concentration of local deformations that methodically succeed each other in time and space. Consequences of these deformations are periodical irregularities in applied force and undulations on material surface. In case of tensile tests this behaviour is well represented by serrations in stress-strain curves and is evident as deformation bands on specimens. Fig. 1 shows a stress-strain curve for our material with a detail that better displays the typical serrations that affect most of the plastic deformation. Force drops are related to global material relaxations because of the establishing of local deformation zones.

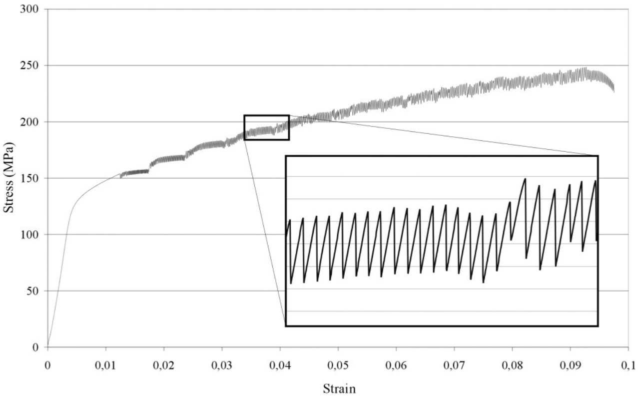

Fig. 1. Stress-strain curve for Al-3Mg alloy at room temperature.

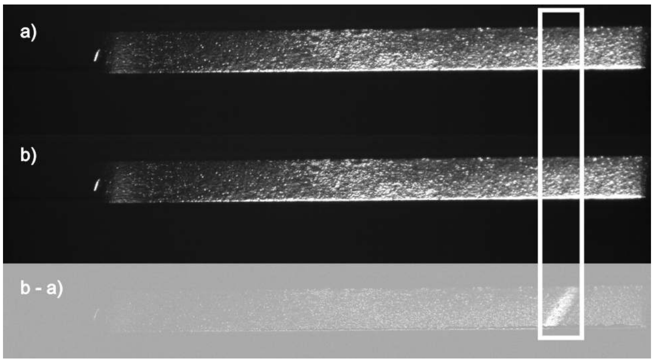

Fig. 2. a) and b): tensile specimen in two successive frames of a video sequence taken at 500fps. The figure underneath is the result of the difference between the two pictures; contrast and brightness have been modified to enhance the band formed in the meantime.

Fig. 2 shows pictures of PLC bands on the specimen taken with a high resolution CMOS camera operated at 500fps. Bands are local reductions of specimen thickness that form a fixed angle to the strain direction. Because of their small depth, in the order of some micrometers, bands are slightly visible and optimal lighting conditions are difficult to obtain. However, the difference between the two greyscale images that is depicted below in Fig. 2 reveals the development of a new band in the time between the two frames. According to the appearing of the regularity of the effect and to the working conditions three types of bands can be distinguished [5]. The so called type A bands have regular, continuous and fast propagations all along the specimen. The related stress-strain curve shows little pronounced serrations. Type B bands have regular but discontinuous propagations, i.e. the propagation proceeds stepwise. Serrations have a much higher frequency and every force drop is related to a propagation step. Type C bands are completely irregular and nucleate randomly inside the specimen. Serrations are frequent, but in the loading phase they present a plastic part too.

A model of the microscopic mechanism of the PLC effect is known as “dynamical strain ageing” and was introduced by Cottrell [6]. It is based on the interaction between dislocations and solute atoms when they have a comparable, but not equal, mobility. Solute atoms tend to concentrate in clouds around the dislocations and to hinder their movement, but dislocations can break away from obstacles because of applied stress. If solute atoms have a sufficiently high diffusion mobility, they can recapture the dislocations, establishing in this way a state of two deformation regimes: a fast regime, when dislocations move freely, and a slow regime, when dislocations are blocked. There are different models about the diffusion mechanisms and they can take place simultaneously or one of them can be prominent under particular conditions [7,8]. The dynamical strain ageing, however, seems not to be sufficient to give a macroscopic description of the phenomenon. A mesoscopic model was then proposed by Hähner, who introduced the long range interaction among dislocations as a necessary condition [9].

Nevertheless, many factors, such as grain dimension, grain boundaries, grain orientation, precipitates, anisotropy and specimen thickness have to be taken into account and several investigations deal with their influence on the appearing of the phenomenon [10-13]. There are, however, relatively few researches focused on the investigation and comprehension of the development and propagation of PLC bands. Besides already mentioned works about PLC band dynamics, other works provide geometrical descriptions of bands; they are mainly based on roughness measurements and on image analysis or video sequences [14,15]. Our new measurement set-up is part of this branch of investigations on PLC effect. At the moment it deals with the dynamics of the effect, but the further development will try to link morphological analysis of bands to the information about their effective deformations.

3. EXPERIMENTAL

The Portevin-Le Châtelier effect is observed by means of an optical extensometer applied to a tensile testing machine.

The PLC effect can occur in polycrystalline ductile alloys, many of them have already been investigated. The material we employ is an Al-3wt%Mg alloy that shows the effect at room temperature. The specimens are cut out from a cold rolled sheet and have a gauge length of 74mm, a width of 4mm and a thickness of 1,5mm. They are tested after 2h annealing at 400°C or 500°C.

Experiments are performed at room temperature with an Instron 1185 material testing machine that has a maximum force of 10kN and can be operated either at a constant strain rate or at a constant stress rate. At the moment we are employing strain rate control within the interval from $5x10^{-6}$ to $5x10^{-4}$ s^{-1}, where type B bands are typical. In the future higher velocities and constant stress-rate control will be explored too. These are conditions for a type A band propagation, generally faster than the type B.

Because the specimens are flat, we can use one side for the extensometer and the other one for the video recording. The extensometer side has to be coated with a pattern of alternating white and black zones in order to subdivide the specimen length into small observation regions. The width of these zones is 1mm, that is the spatial resolution of the system and is comparable to the width of a band. The extensometer is a Schäfter+Kirchhoff SK1024DDE line-scan camera whose sensor is parallel to the machine axis. The camera can be operated with different frame rates in the range between 100fps and 10.000fps; currently the tests are performed at 250fps. Because of the dimension of the machine grips, part of the gauge length remains hidden to the camera and just a length of 55mm can be acquired through a 25mm/f-1,8 objective with a resolution of 61µm/pixel. The captured image is a line with alternated black and white segments. As long as deformation is homogeneous in the whole specimen, the elongation of the segments is homogeneous too. Whenever a local deformation occurs, the related zone undergoes an extension greater than that one of the others. That is the key to determine the time and the position of an arising band.

The algorithm to identify a local deformation calculates for each image the position of all the zones. The position of a zone is defined as its centre-point, i.e. the middle point between its two borders. The position of a border is calculated as the point where the edge crosses a given threshold and a sub-pixel value is reached by means of a linear interpolation between the two pixels whose grey values are immediately below and above threshold. Because of its strong dependence on the threshold value and on image quality, the linear interpolation is not the most appropriated method to calculate an exact edge position, but it is highly reliable, very fast and extremely sensitive. Under optimal lighting conditions, repeated measurements of a stationary zone position give a distribution of values within the range of 0,06 pixel, i.e. a standard deviation of 0,01 pixel. Since the images to process are very simple and subject only to small changes, the precision of linear interpolation is acceptable for our aims of position tracking. Moreover, the position itself is not as important as its change and the interpolation method has been proven to be very sensitive to really small edge displacements and not to be affected by pixel-sampling effects.

The temporal evolution of a zone position during tensile test is shown as an example in Fig.3. The x-axis represents the image number that is proportional to the elapsing time, while the y-axis represents the calculated position in pixel-units. The specimen is fixed at one side and pulled at the other, entailing a displacement of zone centres as effect of the traction. The curve has a growing global trend because the increasing pixel arrangement is in the direction of the applied force. The presence of two periodical patterns characterizes this curve: a set of saw-teeth until image 4800 and then a set of upward steps. Common to both patterns is a sudden position discontinuity, which is related to the formation of a band. These discontinuities occur simultaneously for all the zones. Since the machine has a constant strain rate, in fact, the global elongation of the specimen due to a local deformation reduces the internal stress. The consequent elastic retreat causes an instantaneous displacement of the zones, but with different direction to let the elongation occur in between: the zones before the active region are forced back, the others are forced forward. In the image, the zones on the left side with respect to the active region are pulled back and their positions quickly decrease (saw teeth), zones on the right side are moved forward (steps). The time instant a local deformation takes place can therefore be identified by the occurrence of these discontinuities. Comparing the discontinuities of all the zones at that same moment it is also possible to determine the related position of the local deformation. This is between the two zones for which this discontinuity switches from a saw tooth to a step shape.

In Fig. 4 the curves of three zones are shown together to display their connections; they are shifted closer in order to enhance the extent of jumps. The curves refer to successive zones of the specimen: the first zone is before the second one and this one is before the third one. The abrupt discontinuities occur at the same instants for all the three curves, but the switch from saw teeth to steps happens at different moments. At the beginning all the zones have a saw teeth pattern, then they are on the left side with respect to the deformations. At 19,2s only curve 3 has a step, i.e. curve 3 is now on the right side of the occurred local deformation while curve 1 and 2 are still on its left. At 22,4s curve 2 too is on the right of the new deformation. At 25,6s all the curves are on the right side of the actual local deformation. The physical meaning of this spatial and temporal arrangement is that the local deformation propagates from the right to the left. This is visible in Fig. 5, a location-time map of deformation events for this specimen. The abscissa represents the time in second and the ordinate the position in pixels. Each point corresponds to a deformation event according to the moment and the location of its appearing.

This extensometer is conceptually similar to the laser extensometer already employed by our research group. The laser extensometer works with a scanning frequency of 50Hz and with a zone width of 2mm. The new optical extensometer operates at the moment at 250Hz and with a zone width of 1mm, but it has the potential to reach a scanning frequency up to 10kHz and a zone size of at least 0,5mm. A further development takes advantages of the possibility to run the band detection algorithm in a real-time mode: this is the basis to track the propagation of the bands front with high resolution video sequences. In order to reach

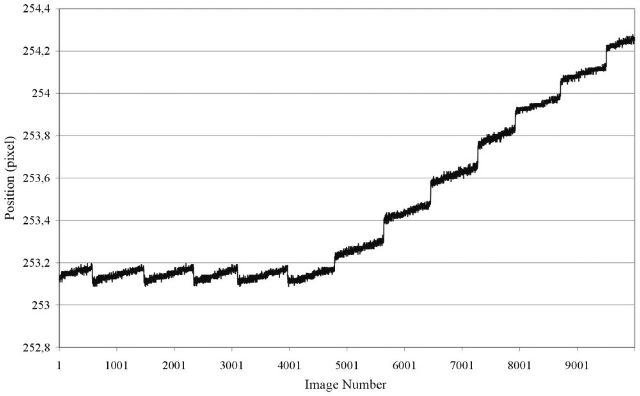

Fig. 3. Evolution of the position of a specimen zone in time. The diagram refers to a time interval of 40s at the scanning frequency 250Hz. Vertical discontinuities represent the moments of band appearing in the specimen. The overall zone displacement is a little more than one pixel (61µm).

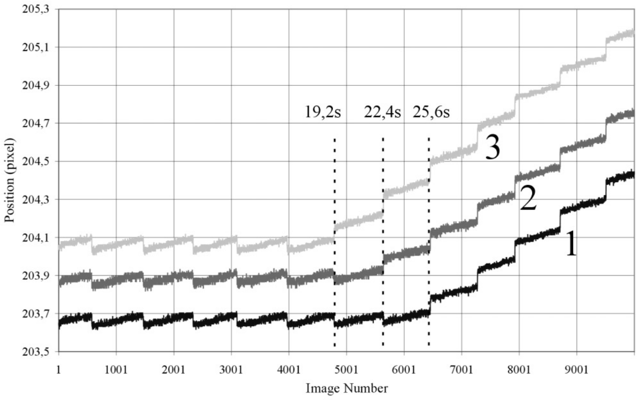

Fig. 4. Synoptic view of the evolving positions of three zones. Initial position of zone 1 is pixel 203; curves 2 and 3 have initial position at pixel 227 and 253 respectively. They are represented shifted close to curve 1.

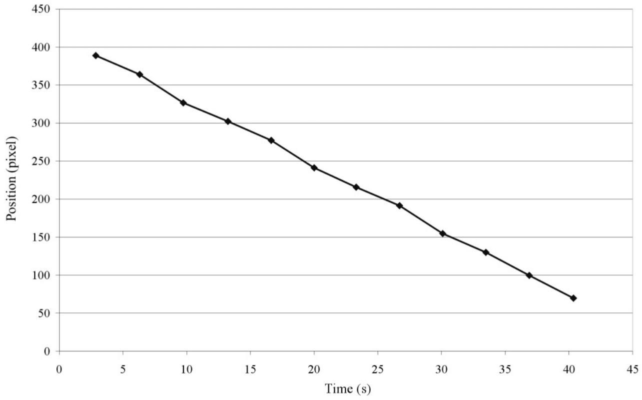

Fig. 5. Location-time map of deformation events for the tensile test of previous figures. A linear propagation crosses the specimen in opposite direction with respect to the traction.

a high image resolution the field of view of a camera has to be relative small. Because only a fraction of specimen surface can be imaged, the camera has to be moved synchronously with the propagating front. In our case the dimension of field of view is about 5x4 mm², comparable to the extension of some bands. The optical extensometer provides the necessary information about deformation position and velocity of band propagation, making it possible to control an actuator that moves the camera.

The most recent cameras with CMOS megapixel sensor are the most suitable ones to record the formation of the bands. Their main advantages are the high frame rate and the possibility to read out areas of interest of the sensor with further increased frame rate. The image frequency reaches up to 500Hz in full frame mode, but it can be dramatically increased reducing the active window of the sensor. A camera tracking of bands propagation of the bands would be a new kind of instrument in this research field and the capture of dynamical processes can be determinant in revealing the mechanisms of the PLC effect.

4. RESULTS

The performed tests have shown the behaviour of the material during the traction. Although the material had always been tested after annealing and its state was then always homogeneous, the PLC effect appeared with a certain irregularity. The general trend shows clean propagations at the beginning, when the material is still slightly deformed, but then it gradually turns to a random band nucleation. The extension of the period of regular propagation is not fixed, it can vary quite a lot, although a 2 minutes length is an indicative value. The velocity of band front is relatively stable throughout a single propagation, but its value can change significantly with successive propagations. The velocity change is usually linked to a change in the waiting time between deformation events, that can last from 0,5s up to 3,5s. The range of detected velocities is in the magnitude order of some millimetres per second, from about 1,5mm/s up to 7,5mm/s.

Fig. 6 shows a location-time map of deformation events for a test at 1x10^{-4} s^{-1}. As visible, a first set of aligned points describes a clean propagation, whose velocity is 4,6 mm/s, but the following sets are increasingly irregular. The velocity rises to 7,5mm/s and in the last set a probable double propagation can to be seen.

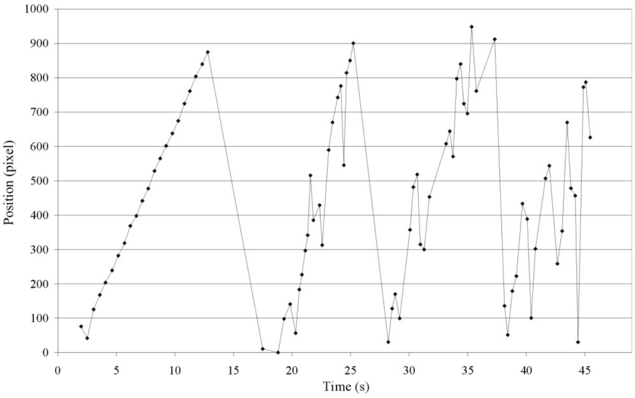

Fig. 6. Series of propagations for a tensile test at 1x10^{-4} s^{-1} constant strain rate. Only the first propagation is regular.

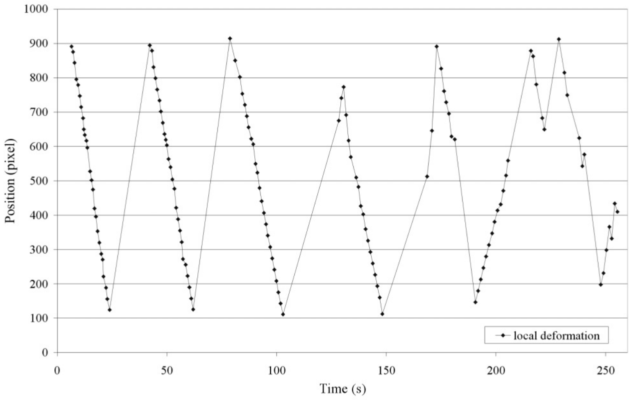

Fig. 7. Series of propagations for a tensile test at the same speed as for Fig. 6., but with a pre-deformed specimen. Now the extension of the period with regular propagations is greater than for the previous figure, but the propagation velocities are lower

In Fig. 7 an analogous curve for a test with the same strain rate is shown. The specimen was previously deformed and then annealed again before the test. In this case there are regular propagations for about 200s and the velocities are all around 2,5mm/s.

The time necessary for the formation of a band, on the other side, is constantly about 0,05s. This is a really small time and is not enough to afford a reaction on camera movement: the camera has to be already at the position of a deformation in order to record it. For this reason the tracking of band formation is solely possible during a clean propagation. Once the position and the constant velocity of the band front has been calculated, the camera can be moved in parallel with it. At the moment, the investigations are mainly focused on the search for the better conditions for regular propagations.

5. CONCLUSIONS

A new optical extensometer has been developed to map the propagation of PLC bands in metal alloys and has been employed to observe type B bands behaviour on Al-3%Mg alloy. This device has a high temporal and spatial resolution for the detection of this dynamical phenomenon and has the potentiality to further increase its scanning rate.

Tracking the band front with a mobile camera has been proven to be a feasible development. Operated in real-time the optical extensometer can control an actuator to move the camera over the band front in order to record video sequences of the propagation. A regular propagation is an important condition for this application.

REFERENCES

[1] Y. Estrin, C. P. Ling, P. G. McCormick, "Localization of plastic flow: spatial vs temporal instabilities", *Acta Metall. Mater.*, vol. 39, no. 39, pp. 2943-2949, 1991.

[2] D. Thevenet, M. Mliha-Touati, A. Zeghloul, "Characteristics of the propagating deformation bands associated with the Portevin-Le Châtelier effect in Al-Zn-Mg-Cu alloy", *Mat. Sci. Eng. A*, vol. 291, pp. 110-117, 2000.

[3] A. Ziegenbein, H. Neuhäuser et al. , "Local plasticity of Cu-Al polycrystals by in-situ observations and FEM simulations", *J. Phys. IV France*, vol. 8, pp. 407-412, 1998.

[4] S. Toyooka, V. Madjarova, Q. C. Zhang, Suprapedi, "Dynamic deformation analysis by ESPI", *Fringe 2001 4th Int. Work. on Aut. Proces. of Fringe Patterns*, pp. 605-612, 2001.

[5] P.G. McCormick, "Dynamic strain ageing", *Trans. Indian Inst. of Metals*, vol. 39, pp. 98-106, 1986.

[6] A. H. Cottrell, "A note on the Portevin-Le Châtelier effect", *Phil. Mag.*, vol. 44, pp. 829-832, 1953.

[7] P. Hähner, A. Ziegenbein, E. Rizzi, H. Neuhäuser, "Spatiotemporal analysis of Portevin-Le Châtelier deformations bands: theory, simulation, and experiment", *Physical Review B*, vol. 65, 134109, march 2002.

[8] F. Chmelík A. Ziegenbein, H. Neuhäuser, P. Lukáč, "Investigating the Portevin-Le Châtelier effect by the acoustic emission and laser extensometry techniques", *Mat. Sci. Eng. A*, vol. 324, pp. 200-207, 2002.

[9] P. Hähner, "On the physics of the Portevin-Le Châtelier effect, part 1 and 2", *Mat. Sci. Eng. A*, vol. 207, pp. 208-223, 1996.

[10] Zs. Kovács, D. Fátay, K. Nyilas, J. Lendvai, "Effect of grain boundaries on PLC plastic instabilities", *J. Eng. Mat. Tecn.*, vol. 124, pp. 23-26, January 2002.

[11] Zs. Kovács, N.Q. Chinh, J. Lendvai, "Orientation dependence of Portevin-Le Châtelier plastic instabilities in depth-sensing microindentation", *J. Mater. Res.*, vol. 16, pp. 1171-1177, April 2001.

[12] D. Thevenet, M. Mliha-Touati, A. Zeghloul, "The effect of precipitation on the Portevin-Le Châtelier effect in an Al-Zn-Mg-Cu Alloy", *Mat. Sci. Eng. A*, vol. 266, pp. 175-182, 1999.

[13] X-M. Cheng, J. G. Morris, "The aniyotropy of the Portevin-Le Châtelier effect in aluminium alloys", *Scripta Mater.*, vol. 43, pp. 651-658, 2000.

[14] W. M. Webernig, E. Pink, J, Król, "Stretcher-strain markings and the fracture of thin sheets of Al-Mg-Alloys", *Z. Metallkde.*, vol. 77, pp. 188-192, 1986.

[15] K. Chihab, Y. Estrin, L. P. Kubin, J. Vergnol, "The kinetics of the Portevin-Le Châtelier bands in Al-5at%Mg alloy", *Scripta Metall.*, vol. 21, pp. 203-208, 1987.

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