LÜDERS BAND FORMATION IN STEEL - VIDEO

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Keywords: Microstructure, microstructural evolution, tensile testing, digital video, Lüders bands, upper yield stress, lower yield stress.

Prerequisite Knowledge: Basic knowledge of the following is required: mechanical properties of low-carbon steels, formation and propagation of Lüders bands, tensile testing, digital video using the PC and basic video editing techniques.

Objectives: The objectives of this paper are:

1. To describe how we made a video showing the formation and propagation of Lüders bands during tensile deformation of a low-carbon steel
2. Provide instructions on how to make a video for classroom instruction
3. Encouraged others to create and share their own videos of in-situ observations or other materials processes.

Also, projects such as this are excellent student laboratory projects and produce course materials that an instructor can use in the classroom, and which the student can show to friends who might be interested in majoring in materials science and engineering.

Equipment: The equipment used to make the videos consisted of the following:

- Oven – An oven capable of reaching 300°C.
- Tensile testing system – in this case an Instron model 4204 (computer controlled, 50 kN capacity)
- Digital camera – A CCD video camera with composite video output.
- Video Capture – The computer used in this project was a 733 MHz Pentium III-based PC running Windows 98. It had 256 MB of SDRAM and a 30 GB ATA-100 hard drive. The video capture board, a miroVIDEO DC30 Pro, was capable of digitizing full motion video at 640x480x24 bits and 30 frames per second (fps).
- Video editing software – Adobe Premiere 5.1
- Optical Microscope – the microscope used in this experiment was a Zeiss-Herrberg stereo-zoom microscope capable of providing magnifications from 5 to 75X and at a working distance of several inches.
- Illumination – Fostec light source utilizing a quartz lamp and ring or dual-light pipe fiber optic illuminators.
- Other Microscopes – an FEI XL30-SFEG scanning electron microscope was used to obtain high-resolution images of the Lüders bands while a metallograph was used to obtain color images of the Lüders bands at ordinary magnifications.

Introduction: Lüders bands formation and propagation are fascinating aspects of the deformation of a number of materials. This can be seen in figure 1 as the curious feature of the stress-strain curve, the upper and lower yield strengths and yield point extension. This behavior is characterized by an initially high yield stress followed immediately by a sudden drop in stress. With continued straining the stress stays nearly constant for several percent strain before normal strain hardening behavior begins. This behavior always elicits questions from students. An explanation involves a discussion that deals with how dislocations break free of the solute atoms, a localized process which produces the Lüders bands which in turn propagate until they cover the whole specimen. Lüders bands may appear as elongated surface markings or depressions, often visible with the unaided eye. Many textbooks contain pictures of Lüders bands we can show to the students, or, we can polish up a specimen and let the students watch the Lüders bands from during a tensile test. If this is not convenient then one can use our video that shows Lüders bands forming and propagating on the surface of a polished steel tensile specimen.

In this video project, specimens of steel were annealed, polished and tensile tested. Changes in the surface of a specimen observed using an optical microscope were recorded using a VCR and a PC-based digital video capture system. In this paper we describe how this was done.

Procedure:

Materials

The steel used in this experiment was a 1-inch (25.4 mm) wide, ⅛-inch (3.175 mm) thick strip of 1018 steel. These were machined into tensile specimens having a gage length of 1.50 inches (38.1 mm) and a gage width of 0.50 inches (12.7 mm).

Heat Treating

The tensile specimens were annealed in air at 300°C for one hour then air cooled. The objective of this heat treatment was to maximize solute locking of dislocations without causing much grain growth.

Specimen Polishing

After heat treating the specimens were mounted in a specially designed holder (figure 2), ground and polished using an automated polisher/grinder (8-inch wheels, 240-600 grit SiC, 6 μm diamond) and finally with 0.05 micron alumina on a flocked cloth (Buehler’s Micropolish B on Microcloth). The result was a set of flat and highly polished steel tensile specimens (figure 3).

Tensile Testing

Tensile testing was conducted using crosshead speeds ranging from 0.6 mm per minute to over 6 mm per minute. In all tests the lower crosshead was stationary while the upper crosshead moved at the specified rate. During each test the load-elongation data was recorded and saved to disk.

Video Capture

Several tests were done to allow us to monitor Lüders bands activity at different magnifications. A stereo-zoom microscope was mounted horizontally and focused on the surface of the specimen. The magnification of each video segment was noted by recording images of a ruler. A color video camera was attached to the microscope’s C-mount adapter and its output was connected to the PC, a VCR (in case the PC video capture failed) and to a color monitor (figure 4). After making a few short test recordings to ensure everything was working properly the video capture system and the VCR were started and a few seconds later the tensile test was started. The video was recorded at the highest available resolution and frame rate (640x480x24-bits, 30 fps).

A total of seven tests were conducted and recorded, many giving poor results due to poor lighting. Proper illumination of the specimen was difficult due to the highly reflective nature of the specimen and the low contrast of the Lüders bands. The original setup consisted of a color camera with a macro lens and a light source consisting of a dual light-pipe illuminator and a polarizer (figure 5). These problems were solved by doing all recordings using the stereo-zoom microscope and a ring illuminator (figure 6). The resulting videos were similar to microstructures seen using dark-field illumination. The specimen itself appears dark with bright edges and the Lüders bands showed up as bright streaks on the otherwise dark specimen.

Video Processing

All video processing was done on the same PC that was used for the video capture. Adobe Premiere was used to create the title screens, transitions and micron bars, to cut and splice the video and to assemble the final video. The final video shows segments of three different tests. It starts by showing the whole specimen as it is deformed. About half way through the video two segments showing the close-up views of individual Lüders bands. The final video was produced in three formats: 640x480x24-bits, 320x240x24-bits and 160x120x24 bits, all at a frame rate of 15 fps. These videos were also accelerated so that their runtimes would be less than the recommended three minutes.

CD-ROM

The videos, the data from the tensile tests, several frames from the videos and SEM and optical microscope images were written to a CD-ROM.

Comments: Videos such as this one are challenging projects and fun to do with students. They have the added benefit of producing something which can be used to help teach other students. This project requires a thorough understanding of the phenomenon, the testing procedures, advanced computer skills and a knack for presenting the results in a straightforward manner. It also requires a degree of creativity and promotes a sense of ownership which motivates students to do their very best work.

This video, like the videos showing the orange peal surface develop in annealed brass that we made a few years ago [1], was meant to be used as a short video clip in which the instructor provides the background information and narration. The appendix at the end of this paper summarizes some of the details of the sharp yielding phenomenon and Lüders band formation.

This video, the tensile test data, and still images may be downloaded from our web site at www.matsci.ucdavis.edu/ meier/NEW-Update2001. Note that the 640x480 video is a 108 MB file and the 320x240 video is in the neighborhood of 40 MB. Download times may be impractical and you will also need enough hard drive space to store these large files. If you would like to get a copy of these videos you can write or email the authors to request copies of the CD-ROM.

References:

1. M.L.Meier, K.H.Ewald, The Underlying Structure of Engineering Materials, Proceedings of the National Educator's Workshop-Update 98, Brookhaven National Laboratory (1998).

Biographical Information:

Michael L. Meier received his B.S. in Materials Engineering from North Carolina State University in 1979 and his M.S. (1986) and Ph.D. (1991) in Materials Science and Engineering from the University of California, Davis. After a two-year post-doctorate position at the Universität Erlangen-Nürnberg in Erlangen, Germany he returned to UC Davis where he is now the director of Materials Science Central

Facilities.

Aaron Broumas is in his junior year at the University of California, Davis and is majoring in materials science. He is proficient in metallography, specimen preparation techniques, scanning electron microscopy and EDS which he learned outside of normal courses. He has yet to take his core materials science courses. Aaron is currently working full time in Materials Science Central Facilities supporting users of and operating our two scanning electron microscopes. He is also engaged in the analysis of dust samples collected over Puerto Rica and in the northern deserts of China.

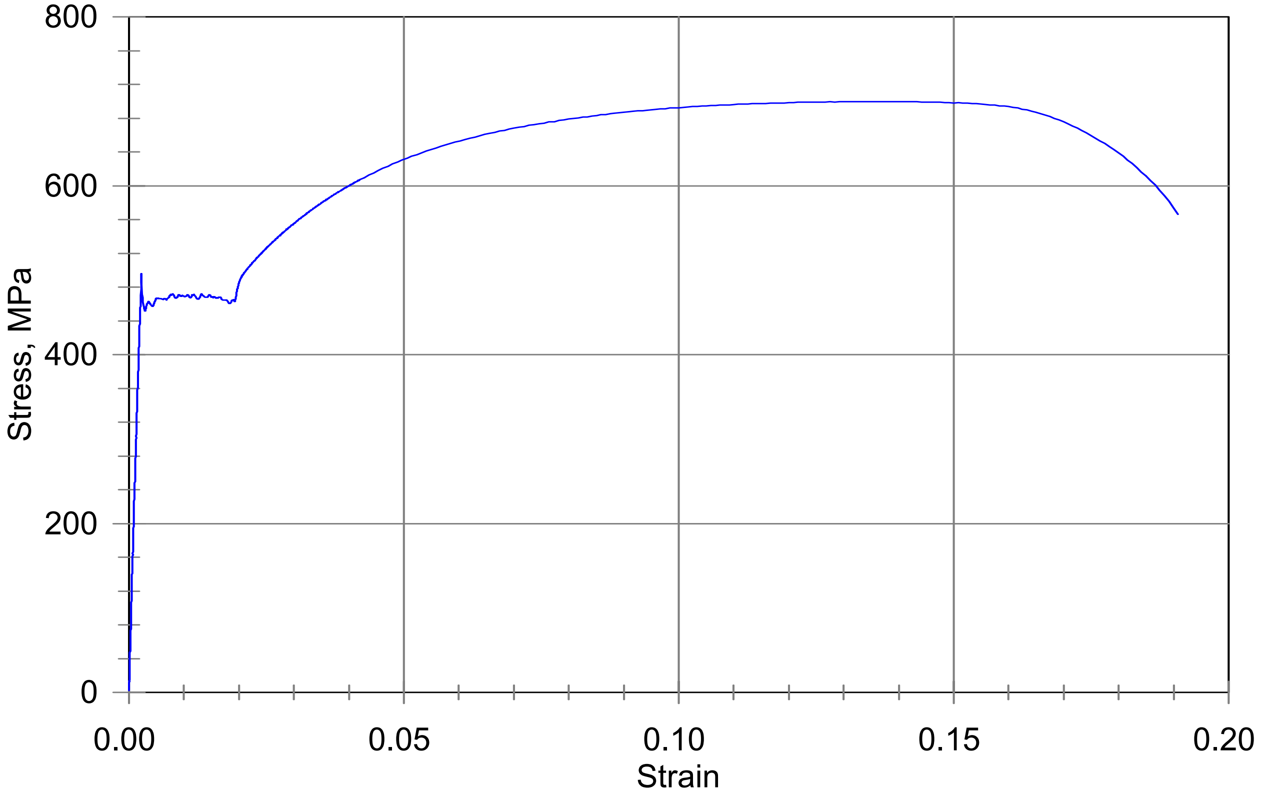

Figure 1 Stress-strain curve for a low-carbon steel. Not the upper and lower yield stresses.

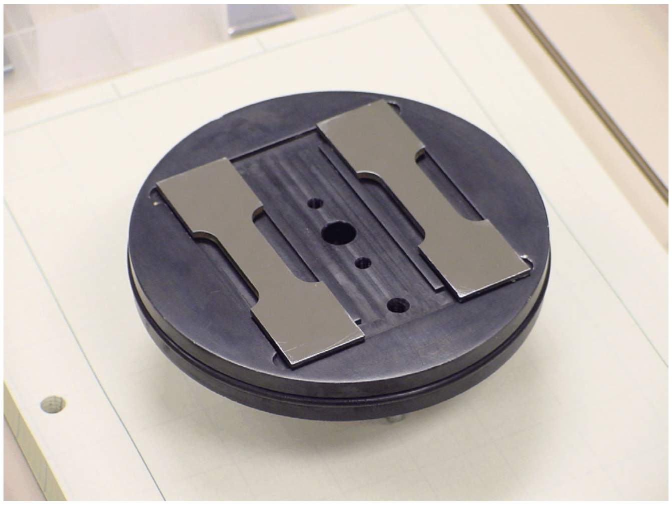

Figure 2 The fixture used to hold the specimens during grinding and polishing.

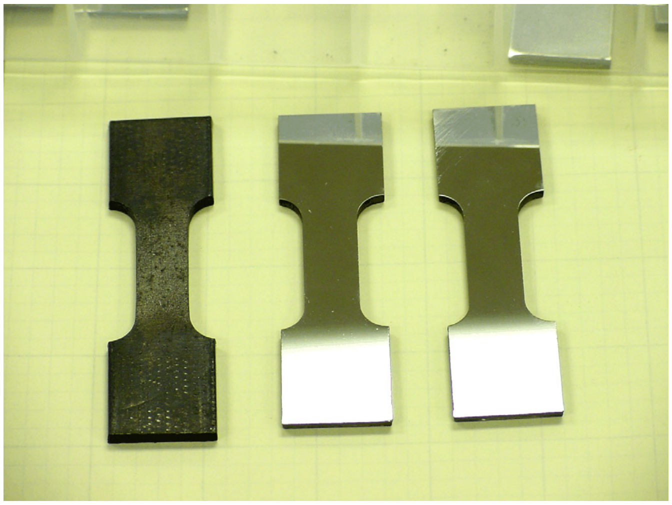

Figure 3 Tensile specimens before and after polishing.

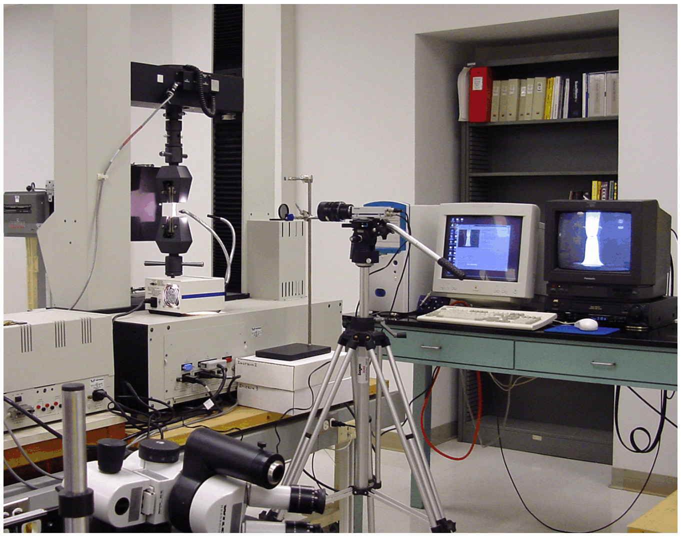

Figure 4 The original setup showing the tensile tester, the camera and illumination setup, the computer, VCR and monitor.

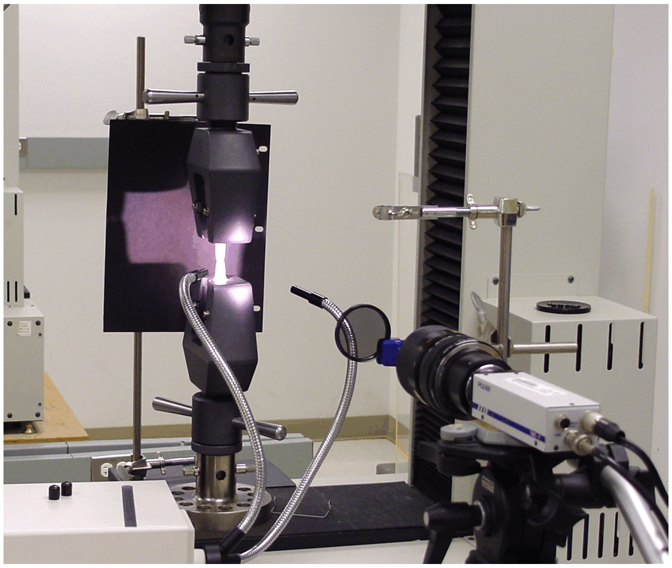

Figure 5 The original camera and lighting setup. The camera and macro lens are mounted on a tripod. The illumination system consists of a dual-light pipe quartz illuminator and a polarizer.

Figure 6 The final setup used for the close-up shots. The ring illuminator provided the best results when videoing the polished steel specimens.

Appendix

This appendix provides a more detailed description of the phenomenon of upper/lower yield point phenomenon and of Lüders band formation and propagation. [1]

General Aspects

Consider a tensile test conducted at a constant rate of strain. Strain rate due to dislocation processes can be expressed as

$$\dot{\epsilon} = \rho b v \qquad (1)$$

where D is the density of mobile dislocations, b is the magnitude of the Burgers vector and v is the average velocity of the mobile dislocations. At the upper yield stress the strain rate is

$$\dot{\epsilon}_U = \rho_U b v_U \tag{2}$$

and at the lower yield stress the strain rate is

$$\dot{\epsilon}_L = \rho_L b v_L. \tag{3}$$

Since the strain rate is constant

$$\dot{\epsilon} = \dot{\epsilon}_L = \dot{\epsilon}_U \tag{4}$$

we can write

$$\frac{\rho_U}{\rho_L} = \frac{v_L}{v_U}. \tag{5}$$

The relationship between stress and velocity is generally written as

$$v = k\tau^m \tag{6}$$

where J is the shear stress acting on the dislocations and m is the strain rate sensitivity. Combining equations 5 and 6 we can express the ratio of the upper and lower shear stress in terms of the ratios of the densities and velocities of dislocations

$$\frac{\tau_U}{\tau_L} = \left(\frac{\rho_L}{\rho_U}\right)^{\frac{1}{m}} = \left(\frac{v_U}{v_L}\right)^{\frac{1}{m}}. \tag{7}$$

This last equation summarizes the general aspects of the upper/lower yield stress phenomenon. At the upper yield stress the mobile dislocation density is low but the average dislocation velocity is high. At lower yield stress there are many more mobile dislocations but they are not moving as fast. Lüders bands are nucleated at the upper yield stress and propagate at the lower yield stress with D_L and v_L representing the deformation that is occurring in a narrow zone ahead of the advancing Lüders band.

Advanced Aspects

Please note the dependence of the ratio of upper and lower yield stress on the strain rate sensitivity *m*. The strain rate sensitivity of a material is measure of the stability of the neck that forms at the UTS which is in turn related to strain hardening index n=, $_{\mathrm{UTS}}$, a measure of the material's resistance to necking. The strain rate sensitivity can readily be measured from the Lüders strain and the initial slope of the stress-strain curve [2].

$$\frac{1}{m} = \frac{\Delta\sigma}{\sigma} - \epsilon_L \tag{8}$$

The early theories of Cottrell-Bilby [3] and others were given in terms of solute atom locking of dislocations. Initially, dislocations are pinned but at the upper yield strength they break away, the mobile dislocation density increases, the dislocation velocity decreases and the stress decreases to the lower yield stress. A later theory proposed by Petch [4] addressed the effect of grain size on the upper yield stress. At the upper yield stress only a few grains contain mobile dislocations and these dislocations move quickly relative to the average velocity for the whole specimen. As more grains acquire mobile dislocations the velocity drops, the macroscopic stress drops and so does the stress required to penetrate grain boundaries. A Lüders band forms and from that point on the number of active grains remains constant as it propagates through the specimen.

The Hall-Petch equation

$$\sigma = \sigma_f + kd^{-\frac{1}{2}} \tag{9}$$

where d is the grain size and F_f is a the inherent strength of the material without grain boundaries, defines the lower yield stress. In Petch's model F_f is expressed as

$$\sigma_f = \sigma_0 + \Delta\sigma_0 \log\left(\frac{1}{Nd^3}\right) \tag{10}$$

where F_0 is the inherent strength when all grains are deforming uniformly and N is the number of active grains per unit volume. The difference between the upper and lower yield stresses is given by the second term in the equation above.

As for the lower yield stress, an important factor is the extension of deformation past or through grain boundaries. The lower yield stress was seen as the stress forcing grain boundaries ahead of the Lüders band and the propagation of the Lüders band involves a process of generating dislocations in the next grain, adjacent to the boundary.

Practical Aspects

It is difficult to measure the true upper yield stress due to practical difficulties in testing, such as the specimen design, grip design, alignment, etc. Consequently the lower yield stress is usually considered the material's yield strength. When these difficulties have been eliminated experiments have shown that the upper yield stress can be twice as high as the lower yield stress.

Lüders bands, also called stretcher strains, are unsightly and may spoil the finish during sheet forming operations. Prior rolling can minimize this, but strain aging can restore it. Strain aging sufficient to cause stretcher strains can occur after a few days at room temperature or only an hour at 60-100°C.

References

1. Honeycombe, *The Plastic Deformation of Metals*, Edward Arnold, London, pp.149-157 (1984).
2. U.F.Kochs, A.S.Argon and M.F.Ashby, *Thermodymanics of Slip*, Pergamon Press, Oxford, pp. 261-264 (1975).
3. A.H.Cottrell and B.A.Bilby, *Proc. Phys. Soc*, **A62**, 490 (1949).
4. N.J.Petch, *The Upper Yield Strength of Polycrystalline Iron*, *Acta Met*. **12**, 59 (1964).