FORMATION OF MICROCRACKS IN HEAVILY DRAWN AND ANNEALED TUNGSTEN

L. Uray and I. Gaal
Research Institute for Technical Physics
of the Hungarian Academy of Sciences
Budapest, Hungary

SUMMARY

The length of heavily drawn non-sag tungsten wires decreases upon free-end torsion, because the slip along the split grain boundaries reduces the length of the samples. The splitting of the grain boundaries upon torsion is preceded by the formation and propagation of Luders bands, and the local variation of the strain at the boundaries of these bands gives rise to internal stresses which promote the splitting of the grain boundaries. When the internal stresses produced by the drawing operation are relieved by a suitable annealing (carried out between 1200 and 1800 K), then the plastic twist is more or less homogeneous along the wires, the twisted sample remains crack-free and the length of the sample increases upon free-end torsion in accordance with the crystallographic texture.

Key words: non-sag tungsten, splitting, torsional Luders bands

INTRODUCTION

Heavily drawn tungsten sometimes splits along the longitudinal grain boundaries upon bending, coiling and drawing. The area of the non-propagating splits and cracks varies between broad limits, and the total area opened up by fracture can be appreciable even at strains much smaller than the strain at fracture. This behaviour is general in BCC metals in that temperature range, where the coarse grained metal is brittle and the samples with elongated fine grains fracture after macroplastic deformation [1].

The present study tries to clarify the formation of propagating and non-propagating cracks and splits in heavily drawn tungsten wires deformed by torsion at the ambient. Previous investigations of the free-end torsion of as drawn non-sag tungsten have shown that localization of the twist leads to the sudden formation of a highly twisted zone, called (torsional) Luders band [2]. The untwisted regions remain crack-free, while the Luders bands contain extended helical splits formed along the originally longitudinal grain boundaries [2]. Upon further twisting the surface strain within the

Luders band remains (virtually) constant and the sample deforms by the movement of the boundaries of the twisted zone, i.e., by the increase of the volume of the Luders band [3].

THE MEASURES OF THE LOCAL TWIST

The formation and spreading of torsional Luders bands can easily be observed on wires, because the local torsion at the free surface can be evaluated by means of the distortion of any marker line, which is originally parallel to the wire axis. The twist of wires with unpolished surfaces can be observed also on the drawing grooves. Thus, Luders bands can be recognized even by visual observation of the natural surface of the wires.

The connection between the distortion of the marker lines and local twist can be derived by considering the ideal torsion of cylindrical samples. It has two important geometrical features:

-- The transversal cross section remains circular and plane.

-- The transversal cross section rotates as if rigid, i.e., the rotation of parallel diameters is proportional to their distance.

Therefore, the local twist of a cylindrical body is characterized by the angle of rotation of two transverse cross sections being at unit distance:

$$\alpha = \frac{\Theta}{L}, \tag{1}$$

where Θ is the rotation angle in radians of two cross sections located at a sufficiently short distance from each other, L, and α is the so-called specific twist. The specific twist is often expressed by the length at which the rotation is a whole turn, i.e.,2π:

$$\alpha = \frac{\Theta}{L} = \frac{2\pi}{h} \tag{2}$$

Since a straight line on the wire surface lying originally parallel to the wire axis will be distorted into a helical line upon ideal torsion,. the pitch of the helix, h, determines also the specific twist according to equ. (2). The specific twist can also be expressed by the helix angle or pitch angle. This is the angle between the axis of the helix and the tangent of the helix. The pitch angle, Ω, does not depend on the actual point of the helix to which the tangent was drawn and can be evaluated from the following expression:

$$tg(\Omega) = \frac{2\pi A}{h}, \tag{3}$$

where A is the radius of the helix and h denotes the pitch. The shear strain on the surface of an ideally twisted wire is:

$$\gamma = \alpha A = \frac{\Theta A}{L} = tg(\Omega)\ . \tag{4}$$

According to (4), the surface shear strain in a twisted wire can be determined either from the pitch or from the pitch angle of the helix formed from the straight marker line upon twisting. The two methods for determination of the surface strain are equivalent, when the specific twist (i.e., the pitch of the helix) changes along the cylinder only slightly. The measurement of the pitch angle gives, however, more coherent results, when the twist changes markedly along the length of the cylindrical sample.

THE NATURE OF LUDERS BAND IN DOPED TUNGSTEN

When heavily drawn doped tungsten is deformed by free-end torsion at the ambient, the twist along the wire is localized into a relatively short zone of the wire (Luders band) in a very early stage of plastic deformation. When the torque is removed just after the appearance of the first Luders band, the drawing grooves are practically parallel to the wire axis ($\Omega<3°$) outside the Luders band evidencing that the plastic strain was very small ($\gamma< 5\%$) outside the Luders band.

The torsional Luders bands in doped tungsten wires have four important features :

-- a.) The Luders bands contain long and short helical splits formed along the originally longitudinal grain boundaries and short transversal cracks ending on grain boundaries. (fig.3.).

-- b.) The helical form and the nearly constant pitch angle of the drawing grooves prove that the twist is nearly constant in the domains between the long helical splits in the bulk of the Luders band (fig.1.)

--c.) The boundaries of the Luders bands are diffuse: i.e., the transition region between the twisted and untwisted zones is in the order of magnitude of the wire diameter (fig.1.).

-- d.) The surface of the catastrophic fracture consists of long splits and short cracks and is always attached to a Luders band.

The axial amplitude of the surface of the catastrophic fracture is large with respect to the wire diameter (fig.2.). In the zone of the catastrophic fracture the drawing grooves change their direction at distances much smaller than the wire diameter due to the presence of very deep splits (fig.2.). The zone of catastrophic fracture started usually with a deep helical split which had also a surface parallel to the free surface (fig.4.) Along this deep split, the helical drawing grooves change their pitch angles at distances much smaller than the wire diameter. In some parts of the surface of the fracture zone, the drawing grooves are parallel to the wire axis (evidencing that this part has not been twisted), while in other parts of the surface the drawing grooves reveal large strains.

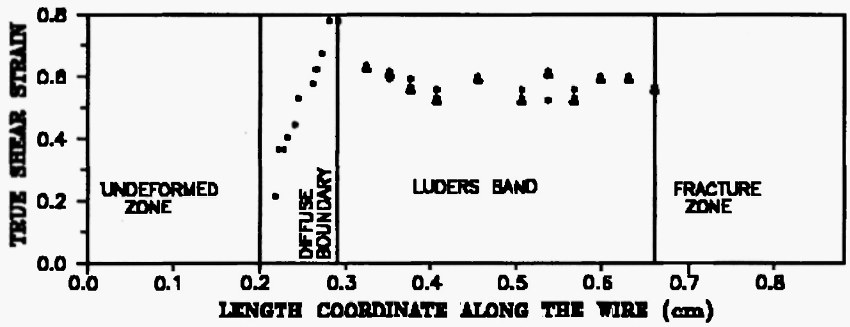

Fig.1. The distribution of twist in a single Luders band formed at the ambient in an unpolished, 150 mm long sample, cut from 0.38 mm diameter as-drawn non-sag tungsten. In this sample only a single Luders band was formed in the middle part of the sample during the whole course of the free-end torsion. The surface morphology of the band was evaluated by means of overlapping scanning micrographs. (In order to test the error of the measurement, the pitch angle was determined at the same place of the wire surface at two different magnifications .)

The relation between the Luders band and the catastrophic fracture can be rationalized as follows. Local splitting suppresses the spreading of the Luders band, as evidenced by the decay of the specific twist in heavily split regions (fig.2.). The decay of twist will give rise to internal stresses, which exaggerate splitting. Consequently, both the decay rate of the specific twist and the peak value of the internal stress increase again and this self-excited process might govern the development of the catastrophic fracture. In spite of this, the catastrophic fracture must be a quite difficult process, because a split part of the wire was coiled onto its remaining part before the sample broke into two pieces (fig.2).

Let us mention that the formation of the transversal cracks is promoted by the stress state caused by the torque, because large tensile tractions act in this stress state on those surfaces, that are nearly perpendicular to the helical marker lines. In contrast, the tractions acting on the helical grain boundaries are compressive in this stress state. This circumstance suggests that the splitting up of the grain boundaries has to be connected with the presence of internal stresses.

Fig.2. In the fracture zone the deep helical splits cause amazingly different deformation modes. (The mark denotes 100 μm.)

LENGTH CHANGE UPON FREE-END TORSION

It has been long known that a wire changes its length upon twisting, when one grip moves freely in the axial direction [4]. The length change as a function of the average specific twist depends on the mechanical state of the non-sag tungsten wires [5]. In stress-relieved wires, the length of the twisted sample usually increases, while in heavily drawn wires the length always decreases. The actual dependence of the length change on the average specific twist seems to be sensitive to various processing parameters [6], i.e., it is not an intrinsic property of heavily drawn tungsten.

In order to clarify the origin of the extrinsic torsional length changes of doped tungsten, let us first summarize the generally accepted rationalization of the intrinsic torsional length change [4]. During free-end torsion without crack formation, the rate of the length change (i.e., the rate of the axial strain) is governed by the rate of the specific twist, provided that the latter is homogeneous along the sample. The ratio of the axial strain and the shear strain, M, depends on the operating slip systems of the material and the crystallographic texture of the sample. Consequently, if the change in the texture upon torsion does not exert a marked influence on M, then the axial plastic strain will be proportional to the specific twist (i.e., to the plastic surface shear strain.) After having realized that the intrinsic axial plastic strain is governed by the texture and the slip systems, one should be convinced that as far as the axial strain is due to intrinsic effects, the length changes in heavily drawn tungsten and molybdenum should be similar, as the crystallographic texture and the slip systems are the same in heavily drawn BCC metals. Since the twisting of heavily drawn molybdenum is homogeneous, it was at hand to choose this material as a reference material for the modelling of the intrinsic behaviour of tungsten in free-end torsion.

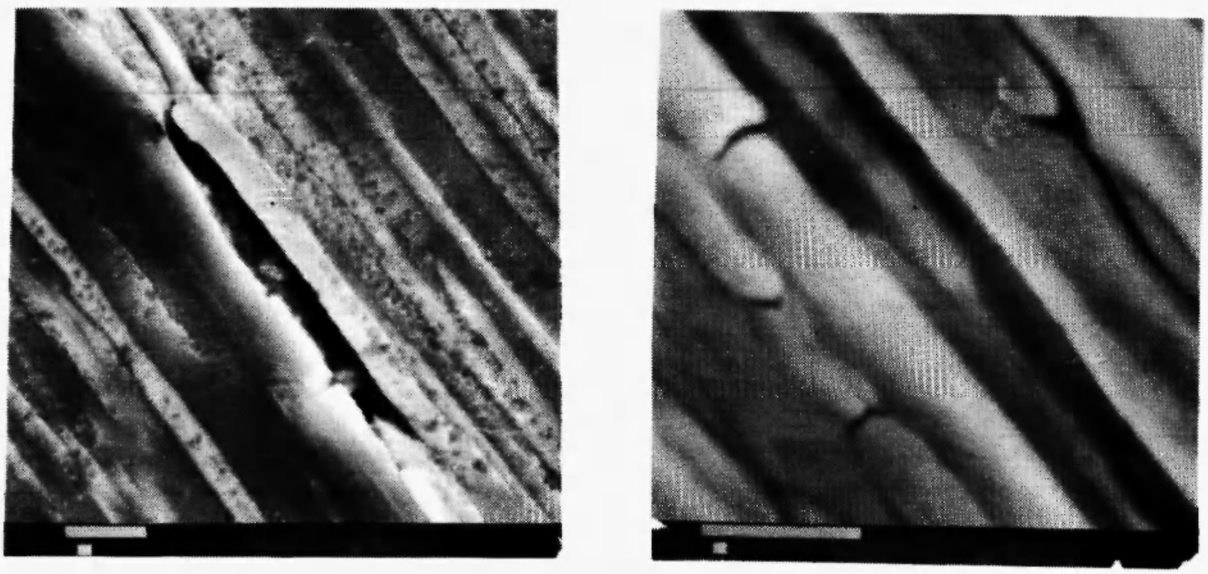

Fig.3. Sometimes splitting is stopped at very short distances. The cracks, which cross the helical grain boundary splits perpendicularly, are always short. Their length varies between 1 μm and 0.5 μm. (The mark denotes 100 μm.)

The length of the heavily drawn 0.4 mm diameter molybdenum wires increased upon free-end torsion. The twist was homogeneous along the sample and the axial strain was nearly proportional to the surface strain, i.e., the axial strain was not too sensitive to the change of the crystallographic texture connected with the torsion. We may, thus, conclude: in tungsten with a <110> texture the axial strain would increase linearly with the specific twist, if it were governed by intrinsic mechanisms through texture and the slip systems and any deviation from this basic behaviour should be explained by the influence of extrinsic factors, like internal stresses, formation of cracks, etc.

This conclusion is supported also by other observations:

1.) Stress-relieved doped tungsten wires undergo elongation upon free-end torsion, and the axial strain is nearly proportional to the torsional surface strain, provided that the specific twist is really constant along the sample.

2.) The torsional ductility of stress-relieved doped tungsten is similar to that of as drawn molybdenum wires: the surface strain at fracture amounts to γ=1.5-1.7 in both materials.

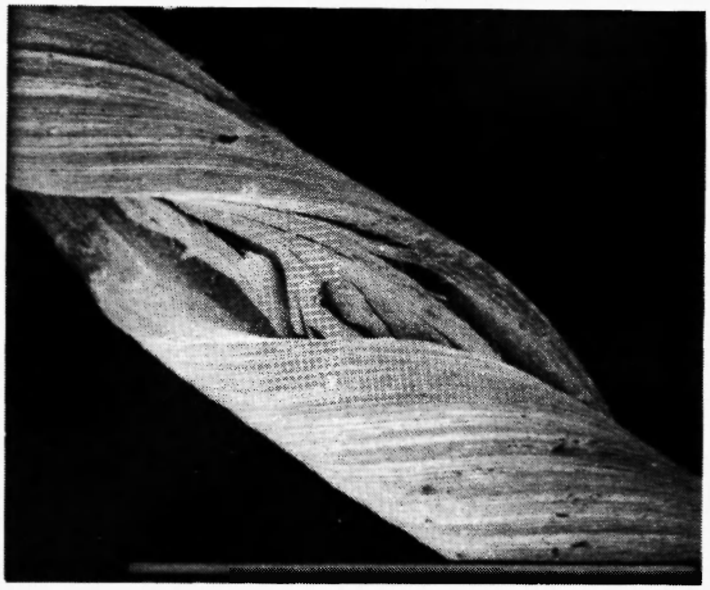

Fig.4. The splits formed upon unidirectional twist open up, when the direction of the twist is reversed.

The decrease in length upon free-end torsion can be ascribed to the presence of long helical splits, because the slip along the lips of a split should decrease the length of the sample. To prove the macromechanical origin of this kind of a slip, a slotted cylindrical bar having a diameter of 6 mm was prepared from brass. (The slot was 10 cm long, about 1 mm wide and 5 mm deep.) The length of this bar decreased upon free-end torsion and the slot closed. As a consequence, the slot was able to transmit torque upon unidirectional torsion. We believe that this model experiment supports the conclusion that upon free-end torsion the helical splitting of tungsten wires will reduce the length of the wires, on the one hand, and that on the other hand, the splits will remain closed upon unidirectional torsion and able to transmit torque. Therefore, even large scale splitting will not lead to fracture at low strains.

Let us realize that reversed twist will open up the lips of the helical splits markedly (fig.4.), and the torque upon reversed twist will be localized at the kernel of the wire. As a consequence, unidirectionally pretwisted wires should fail upon cyclic deformation at low cycles. This prediction is in full accordance with the observation and supports the proposed mechanism.

THE ORIGIN OF THE LUDERS BANDS

On as-drawn wires the formation of the Luders bands was always accompanied by a marked drop in the torque. The details of the Luders band formation should be complex, because the torque at which Luders bands were formed varied within a wide range, even when the samples were cut consecutively from a 1 m long wire (fig.5). The differences in the evolution of the torque drop correspond also to differences in the morphology of the Luders bands. The abrupt torque drop (fig.5a) is accompanied by the appearance of a Luders band containing a helical split which was at least as long as the diameter of the wire. When the torque drop is diffuse (fig.5b), the splits in the Luders bands are relatively short.

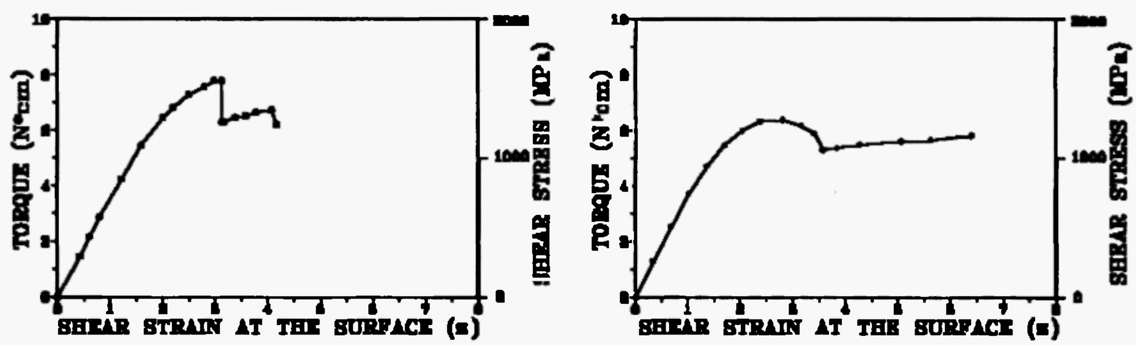

Fig.5 The appearance of the Luders bands is simultaneous with a torque drop on the torsional flow diagram. (The samples were 0.38 mm thick as drawn non-sag tungsten wires.)

The torque drop has three general features:

---1.) The torque drop always takes place in the plastic region of the flow.

---2.) The torque drop is always connected with the appearance of a Luders band.

---3.) The modulus derived from the elastic part of the torsional flow curve is close to the elastic modulus, i.e., the splits and cracks which are eventually present in the samples before the torsion testing are not extended enough to affect the modulus.

We believe that this observation substantiates the assumption that the splitting of the longitudinal grain boundaries is a consequence of the inhomogeneous stress state at the boundaries of the

Luders bands. The dominance of the flow localisation (i.e., Luders band formation) in the splitting of as-drawn non-sag tungsten urged us to search for the reasons of the flow localisation in torsion. It seems to us that the formation of the observed torsional Luders bands can be explained in terms of the macroplastic theory of flow localisation [7], which states: in order to get homogeneous twist the effects of local longitudinal inhomogeneities in internal stress, hardness, wire diameter, etc. have to be suppressed by the hardening rate. According to the torsional flow diagrams, the hardening rates of the 0.38 mm diameter non-sag tungsten wires are lower both in the as-drawn and in the stress-relieved state than the hardening rate of an as-drawn 0.4 mm diameter undoped molybdenum wires. The torsional hardening rate, defined as $\tau^{-1}d\tau/d\gamma$, amounts in stress-relieved tungsten and in as-drawn molybdenum to 0.013 and to 0.1, respectively, while the hardening rate of stress relieved-tungsten must be higher than that of as drawn tungsten, because the flow stress decreases markedly upon stress relief. Since the twist remains homogeneous in a sample with given fluctuation in the internal stresses and in the microstructure only as long as the rate of work hardening is high enough, the difference in hardening rate is in accordance with the observation that doped tungsten is much more prone to heterogeneous twist than molybdenum, and stress-relieved non-sag tungsten deforms by more or less homogeneous twist, while in as-drawn non-sag tungsten Luders bands are formed.

REFERENCES

[1] Ashby, M.F., Gandhi, C.,Taplin, D.M.R.: Acta Metall. 27 (1979) 699

[2] Szokefalvi-Nagy, A.: Scripta Metall.16 (1982) 1009

[3] Uray, L.: J. Mat. Sci. Eng. 112A (1989) 89

[4] Bailey, J. A.: Mechanical Testing (Eds.: Newby, J. R. et. al.) Metals Handbook Vol.8. ASM Metals Park, Ohio, 1985 p. 143

[5] Neugebauer, J.:Realstructure und Eigenschaften von Reinststoffen (Eds. Kunze, J. et al.) Akademie Verlag, Berlin 1965 p. 755

[6] Nagy, Gy. and Uray, L.: (in this volume)

[7] Stuwe, H. P. and Asbeck, H. O. : Arch. Eisenhuttenwesen 40 (1969) 125