The effect of strain rate on steel wires failure during cold drawing

F. Gálvez, J. M. Atienza, J. Ruiz and M. Elices

Departamento de Ciencia de Materiales, Universidad Politécnica de Madrid. Ciudad Universitaria s/n, E-28040 Madrid, Spain

ABSTRACT Wire fracture during processing causes important losses for the drawing industry. A lot of failure criteria have been developed in recent years in order to predict and avoid this problem. Nevertheless, their success is limited up to now. One of the reasons may be that in these models the mechanical behaviour of the material is represented only by the stress-strain curve obtained in conventional tensile tests (low strain rate). However, in modern industrial processes, drawing speeds can reach values of 10-100 m/s, which produces strain rates of 10^3 s^{-1} or even 10^4 s^{-1}. The aim of this work is to study the strain rate effect on the mechanical behaviour of a ferritic steel wire. For that purpose, conventional tensile tests (low strain rate) and Hopkinson bar tests (high strain rate) have been performed. The experimental stress-strain curves have been used to implement a numerical model of the drawing process taking into account the strain rate effect. Numerical results show that the strain rate has a remarkable influence on the material flow in modern drawing processes. If this effect is not taken into account, the calculated values for the drawing force, the friction coefficient and the stress and strain fields may be not reliable, leading to wrong failure predictions.

INTRODUCTION

Drawn steel wire is a widely used material in prestressed concrete, in mining and fishing cables and as fine wires for tyre reinforcement in cars. These wires are obtained by the cold drawing process, which consists of reducing the section of a bar by pulling through a conical die.

Wire fracture during the manufacturing process causes important losses for the companies. This has lead to the development of models with the aim of understanding how the material behaves during section reduction and avoiding undesired fracture [1-10].

In drawing, the first studies appeared in the 30's by Jenison [1]. He showed that die design was one of the most important factors affecting failure. There have been analytical approaches using the theorem of the upper limit by Avitzur [2] as well as experimental work [3]. The results of this investigations showed that the stress triaxiality at the wire axis is one of the main factors that favour failure initiation. Studies by Rogers [4] showed that the damage depends mainly on the hydrostatic stress component, die geometry, section reduction and friction conditions.

The advances in numerical techniques and the need for improving productivity have increased the interest on ductile failure criteria to predict the failure initiation in cold drawing. A large amount of failure criteria have been proposed in recent years [5-10]. These criteria use the results obtained with the finite element analysis of the process. All of them are based on the same idea: fracture occurs when a damage parameter reaches a threshold value. Depending on the model, this damage parameter is a function of the drawing force, the maximum stresses or the hydrostatic stress component.

Clift [11] and Wifi [12] tried to compare the results of these models with experimental values. They showed that the validity range of different failure criteria is limited. This has also been demonstrated for others [13-15]. In addition, some of the studies are based on experimental results performed in the laboratory, far away from actual drawing production.

In the above-mentioned models, the mechanical behaviour of the material is represented by the stress-strain curve obtained in conventional tensile tests (low strain rate) [5-10]. However, in modern drawing processes, drawing speeds can reach values of 10 to 100 m/s (for fine wires in the last drawing steps), which produces strain rates of 10^3 s^{-1} or even 10^4 s^{-1}.

The aim of this work is to study the strain rate effect on the mechanical behaviour of a ferritic steel wire at different stages of the drawing process. For that purpose, conventional tensile tests (low strain rate) and Hopkinson bar tests (high strain rate) have been performed. The experimental results have been used to implement a numerical model of the drawing process taking into account the strain rate effect.

EXPERIMENTAL.

Two types of cold drawn wires with a low carbon content (0.05%) supplied by Bekaert have been studied (Table 1). The first one, referred to as LCA, has been annealed after drawing. The second one, LCD, has been obtained after a 75% section reduction by cold drawing in several steps.

The mechanical properties of the wires obtained from quasi-static tensile tests are given in Table 2, where each value is the mean of five tests.

High strain rate testing

The experimental work at high strain rate has been carried out using the Split Hopkinson Pressure Bar (SPHB) technique. This procedure is widely extended and is capable to obtain the strains and stresses histories. So, the full stress-strain behaviour can be determined at high strain rates (around 1000 s^{-1}) [16-18].

TABLE 1. Wires studied.

Material	%C	Treatment	Diameter (mm)
LCA	0,05	Annealed after drawing	3,00
LCD	0,05	Drawn	3,08

TABLE 2. Mechanical properties of the wires.

Material	Yield Strength 0,2%	Tensile Strength	Max. Strain
LCA	210 MPa	294 MPa	32,0 %
LCD	575 MPa	578 MPa	0,6 %

The experimental testing device of the SHPB used in this work is shown in Figure 1. It consists in an air gun and a long rod projectile propelled by compressed air. The projectile impacts with the first of two steel bars, both instrumented with strain gages and acting as load cells. The specimen is placed in between the bars. The configuration of this equipment has been specially designed to test small size specimens. The projectile employed is a 180 mm length and 8 mm diameter hard steel rod. The bars are made of the same material and diameter but they are 200 mm length. This equipment in its current configuration is capable to perform tests of 40 μs of duration at strain rates around 1000 s^{-1}.

The testing specimens were short cylinders (4.5 mm length and 3 mm diameter) obtained directly from the wires. A detail of the specimen placed between the steel bars is shown in Figure 1.

Five tests of each wire have been performed. The strain rate achieved ranged from 1000 to 3000 s^{-1}. A comparison between the stress-strain curves obtained from tensile tests and Hopkinson bar tests is given in Figures 2 and 3 for the two wires studied.

Fig. 1: Experimental testing device used in the high strain rate tests. Detail of the specimen location in the testing device.

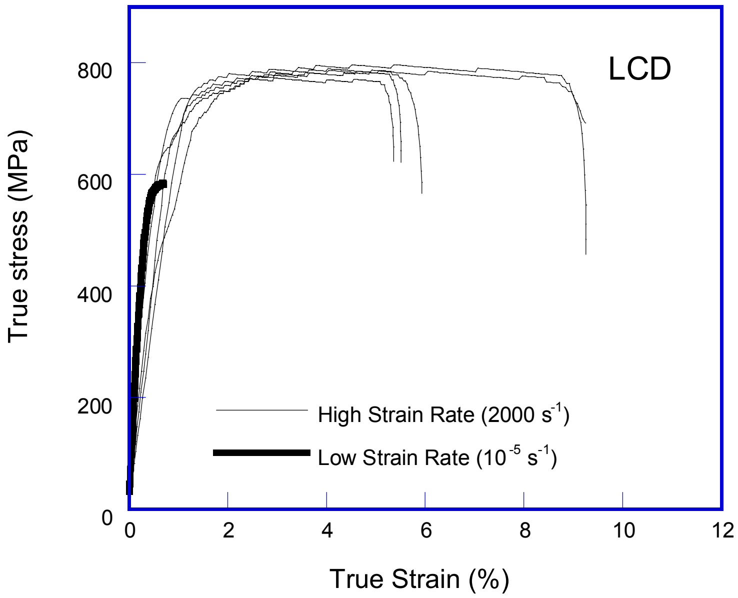

Fig. 2: Stress-strain curves obtained for LCD wires

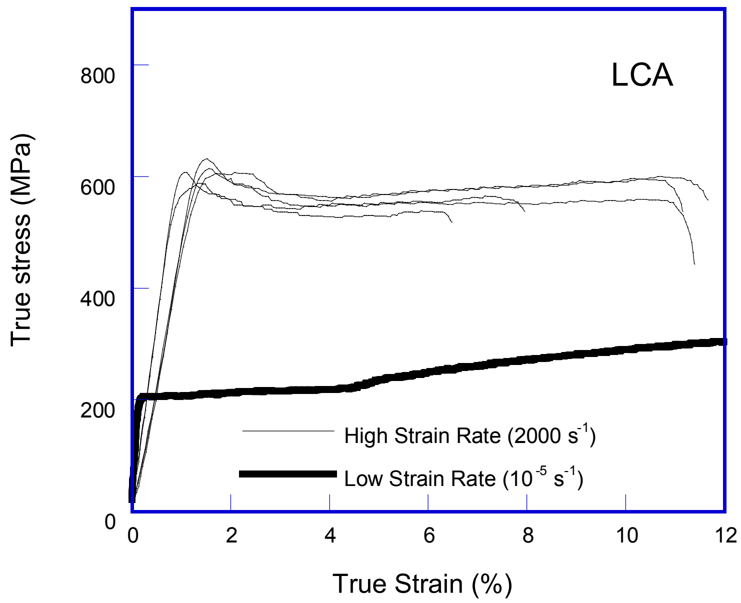

Fig. 3: Stress-strain curves obtained for LCA wires

At high strain rate the yield stress of the annealed wires triples, while it is increased over 30% for the drawn wires. These results agree with previous works of Tanimura [19] and Berbenni [20] because in BCC materials the influence of strain rate decreases as strain increases. Focusing on the annealed material (LCA), the thermal treatment has restored the mechanical properties producing an effect of memory loss of the deformation process. On the opposite side, the drawn wires (LCD) have been subjected to large plastic strains, making the material less sensitive to strain rate.

NUMERICAL MODELLING.

Influence of the strain rate on drawing process.

The results obtained in section 3 have shown that ferritic steel wires are very sensitive to strain rate. A numerical model using the code ABAQUS [21] was developed to study the influence of strain rate on drawing parameters. It reproduces the passing of the wire through a drawing die. The model takes into account the strain rate by using different stress-strain curves at different strain rates.

Wires have been modeled as an elastoplastic isotropic material including strain hardening. The input data are the stress-strain curves at different strain rates. The temperature influence on the material behavior has also been included.

Drawing process has been simulated by forcing the wire to pass through the die and imposing the displacement of the front end of the wire. That is a realistic approach because in the real process the wire is forced to pass through the die by pulling from the point.

The die has been modelled as an elastic material with an elastic modulus of 600 GPa, which is the usual value for tungsten carbide. The contact between the wire and the die has been reproduced with a Coulomb friction coefficient, which ranges from 0.01 to 0.2 in industrial practice.

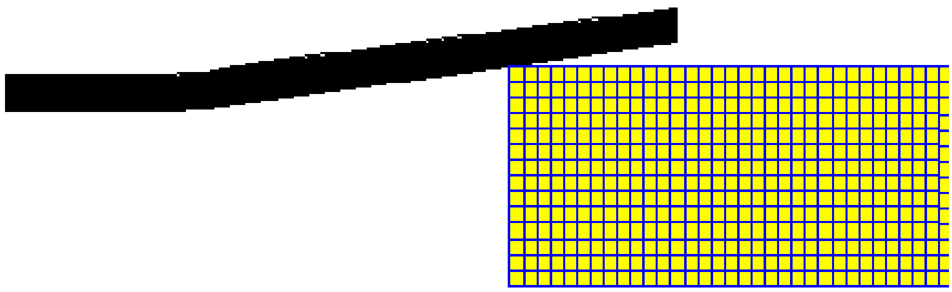

Fig. 4: Finite element mesh used for modelling of cold drawing.

The finite element model interpolates between the stress-strain curves obtained from the tests at different strain rates, using a modified Johnson-Cook material model as proposed by Tanimura [19] for this kind of materials. In every calculation step the code calculates the strain rate in each element, taking it into account for its mechanical properties.

Drawing force checking.

Measurements of the drawing force were used to check the numerical modelling results. Values have been obtained from actual drawing process at the Research Centre of Bekaert by drawing annealed wires at velocities of 5 m/s while measuring the back pull force.

A comparison between the numerical results and the actual drawing measurements is given in Table 3. The data obtained without taking into account the strain rate effect are represented in third. The ones obtained by including the strain rate effect are included in the fourth. It can be observed that the agreement is much better when strain rate effect is taken into account.

TABLE 3. Comparison between actual drawing forces and numerical results with and without strain rate effect.

Actual drawing process		Numerical modelling	
Max. Force (kg)	Min. Force (kg)	No Strain rate (kg)	Strain rate effect (kg)
79,51	77,18	63,20-64,80	78,05-79,10
68,39	66,33	53,12-55,05	69,03-70,05
75,71	73,08	61,15-62,70	74,30-75,45
60,59	58,49	45,20-46,30	61,20-62,35
55,34	53,29	41,34-42,12	54,80-55,78

CONCLUSIONS.

It has been demonstrated that the mechanical properties of ferritic steel wire are highly sensitive to strain rate. Numerical results show that the strain rate has a decisive influence on the material flow in modern drawing processes. If this effect is not taken into account, the calculated values for the drawing force, the friction coefficient and the stress and strain fields may be not reliable, leading into wrong failure predictions.

Ductile failure criteria used to predict wire fracture during drawing are based either on drawing force, maximum stresses or the hydrostatic components of stress. The results of this work show that it seems to be necessary to take into account the strain rate effects to achieve accurate predictions in industrial practice.

ACKNOWLEDGEMENTS.

The Spanish Ministry of Education is gratefully acknowledged for supporting this research through the project FEDER 2FD1997-1513. The authors are very grateful for the help of Mr. Javier del Río and Mr. Feng Mei, from Bekaert, and for the useful comments of Dr. Shen He, from MTM, KU Leuven.

REFERENCES.

1. Jenison H.C. (1930) *Inst. Met.* **97**.

2. Avitzur, B. (1968) *ASME Journal of Engineering for Industry* **90**, 79.
3. Orbegozo, J.I. (1968) *Annals of the CIRP* **16**, 319.
4. Rogers, H.S. (1971) *Metal forming: Interrelation between theory and practice*. Plenum Press, Nueva York, 1971.
5. Oh, S.I., Chen, C.C., Kobayashi, S. (1979) *ASME Journal of Engineering for Industry* **101**, 36.
6. Gurson A.L. (1977) *ASME Journal of Engineering Materials and Technology* **99**, 2.
7. Gelin, J.C., Oudin, J., Ravalard, Y. (1985) *Annals of the CIRP* **34**, 209.
8. Aravas, N. (1986) *Journal of the Mechanics and Physics of Solids* **34**, 55.
9. Mathur, K.K., Dawson, P.R. (1987) *Mechanics of Materials* **6**, 179.
10. Tang, J., Wu, W.T., Walters, J. (1994) *Journal of Materials Processing Technology* **46**, 117.
11. Clift, S.E., Hartley, P., Sturgess, C.E.N., Rowe, G.W. (1990) *International Journal of Mechanical Science* **38**, 1.
12. Wifi, A.S., El-Abbasi, N., Abdel-Hamid, A. (1995) *Materials Processing Defects*, Elsevier, Amsterdam, 1995.
13. Komori K. (1999) *International Journal of Mechanical Science* **41**, 1499.
14. Reddy, N.V., Dixit, P.M., Lal, G.K. (2000) *International Journal of Machine Tools & Manufacture* **40**, 95.
15. Ko D., Kim B. (2000) *Journal of Material Processing Technology* **102**, 19.
16. Kolsky H. (1963). *Stress Waves in Solids*. Ed. Dover, 1963.
17. Davies, E.D.H., Hunter, S.C. (1963) *Journal of the Mechanics and Physics of Solids* **11**, 155-179.
18. Zukas, J.A., Nicholas, T., Shift, N.F., Gresczuk, L.B., Curran, D.R. (1982). *Impact Dynamics*. Ed. John Willey and Sons, 1982.
19. Tanimura, S., Mimura, K., Zhu, W.H. (2000) *Key Engineering Materials*, **177-180**, 189-200.
20. Berbenni, S., Fauvier, V., Cayssials, F., Lemoine, X., Berveillar, M. (2000) Advances in Mechanical Behaviour Plasticity and Damage. Proceedings of EUROMAT, 2000.
21. Hibbitt, Karlsson, Sorensen (1998). *ABAQUS user manual. Version 5.8.*