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Understanding Flexural and Tensile Moduli of Small Drawn Wires

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The mechanisms that are involved in the drawing process and in bending explain why manufacturers commonly use a dedicated flexural modulus.

Many mechanical components as springs, use small mechanical drawn wires. Small drawn wires undergo manufacturing processes that alter their mechanical properties. While manufacturers often designate distinct elastic moduli for tension and bending in wires smaller than one millimeter, scientific consensus recognizes the Young modulus as the fundamental measure. This study aims to elucidate the drawing process and bending mechanisms, explaining why wires might exhibit lower stiffness than anticipated via the common Young modulus, leading to the prevalent use of a specialized elastic modulus in bending.

A first simplified Finite Element Simulation of the drawing process, with a constant Young Modulus, enables to estimate the material state when it is delivered to manufacturers. Then the simulation continues with a tensile test or with a bending test. We can see that, as identified by manufacturers, the wire exhibits a stiffness that corresponds to the Young modulus with the tension test but the linear behaviour in bending shows a lower stiffness. A deep analysis of the simulations shows that this is due to the fact that the material is highly plastically deformed during the drawing process and that an inner part (under the surface) of the wire is directly plastically deformed in compression when the bending test begins. This amount of material in the wire that works plastically (even if the global behaviour of the wire is linear) tends to decrease the overall stiffness of the wire and induces the use a specific elastic modulus in bending in a homogenous equivalency.

Introduction

Small cold drawn wires are extensively used in mechanical systems. Some material with structural effects can exhibit flexural modulus and tensile modulus that can differ from the Young modulus such as composite materials[1].

The elongation of grains and reduction in diameter during drawing impart a needle-like shape to the wire's grains, resulting in pronounced microstructural anisotropy between cross-sections and longitudinal views, as clearly shown in **Figure 1**[2]. This inherent anisotropy suggests potential differences in mechanical properties, specifically in flexural and tensile moduli.

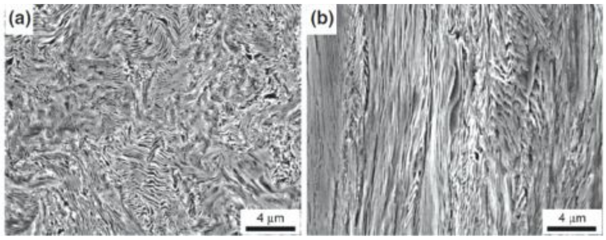

Figure 1: Anisotropy between the cross-sectional area (a) and the longitudinal cross-section (b) of a drawn wire[2].

Moreover, the drawing process can induce axial residual stresses in the wire[3], creating a complex stress state within the material as shown in **Figure 2**.

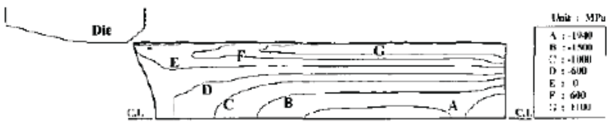

Figure 2: Gradient of residual axial stress after drawing[3].

Detailed studies reveal surface tension and central compression in drawn wires post-drawing[4] (see **Figure 3**).

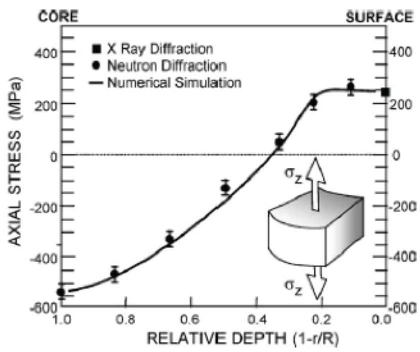

Figure 3: Evolution of axial stress after drawing[4].

These residual stresses, combined with grain deformation, potentially impact the structural behavior of small cold drawn wires.

In order to show why manufacturers and engineers commonly use tensile and flexural moduli instead of a unique Young Modulus, an experimental study that highlights the behaviour of a small cold drawn wire in a tensile and a bending test is first presented. Next a finite element study that first approximates the drawing process and secondly simulates tensile and bending tests is proposed. The FEA should enable to understand the phenomena involved. Afterwards, conclusions are presented.

Experimental Study

A 0.8 mm diameter stainless steel wire, conforming to *AISI 302* standards, was subjected to tensile and bending tests. Its ultimate tensile strength is between 2100 and 2415 MPa and its Young modulus is 180 GPa.

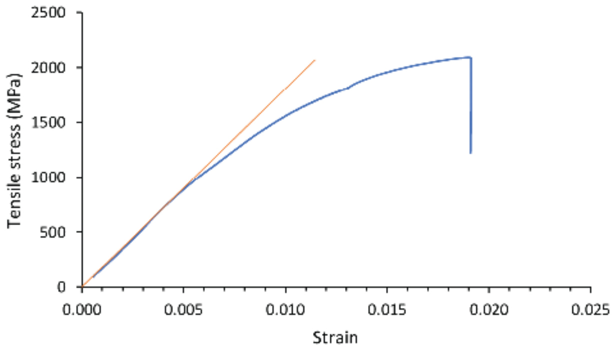

Figure 4: Tensile test of a 0.8 mm diameter wire.

The experimental tensile curve[5] is presented in **Figure 4**. It exhibits a linear behavior which induces a tensile modulus E_t = 182 GPa, closely aligning with the theoretical Young modulus of 180 GPa.

Then a three-points bending test is performed to evaluate the flexural modulus. This experiment has been conducted on a dedicated test bench detailed in **Figure 5**. The Andilog sensor has a 50 N capacity and the maximum axial displacement is 300 mm. In the tested case, the distance between axis is L = 22.3 mm.

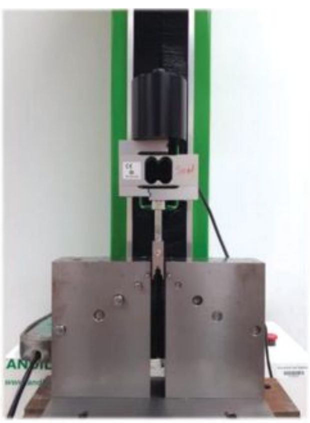

Figure 5: Bending test bench.

The obtained load/deflection curve is presented in **Figure 6**. The common formula of mechanics of materials (Euler–Bernoulli equation for beam bending) can be exploited on the linear behavior to identify the flexural modulus E_f.

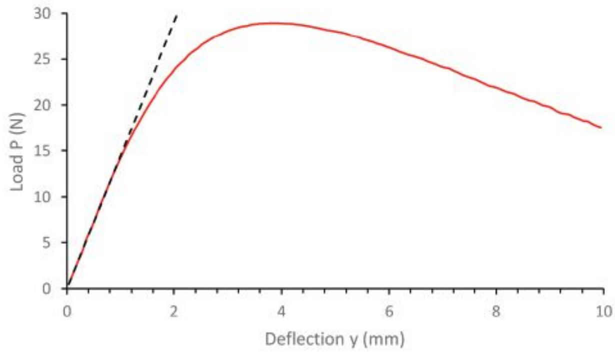

Figure 6: Bending test curve of a 0.8 mm diameter wire.

$$E_f = \frac{P}{y}\frac{L^3}{48\, I_y}$$

(1)

With:

(2)

$$I_y = \frac{\pi D^4}{64}$$

In our case D = 0.8 mm induces I_y = 0.0201 mm^4. Moreover, as L = 22,3 mm, equation (1) enables to calculate the flexural modulus. The three-point bending tests thus demonstrated a flexural modulus (Ef) of 166 GPa, noticeably lower than the Young modulus, as commonly observed in manufacturer data.

Finite Element Analysis

The previous section has shown that a small cold drawn wire can exhibit at the same time, a tensile modulus that is equal to the Young modulus but a lower flexural modulus. The goal of this section is to perform a finite element analysis (FEA) with a simplified drawing process to understand this phenomenon.

The FEA is performed with Abaqus Standard (implicit), C3D20R elements (A 20-node quadratic brick, reduced integration) and 12 elements in diameter. The mesh is illustrated in **Figure 7a** and the material properties are presented in **Table 1**. The simulation exploits multilinear kinematics hardening in order to simulate the Bauschinger effect (not the same behaviour in compression and in tension)[6]. A plane symmetry is exploited to decrease the computing time.

The first step of the simulation is dedicated to the drawing process. The wire is pulled true a simplified die as illustrated in **Figure 7b**. Before drawing the initial diameter is 0.84 mm and the final diameter after drawing is 0.804 mm.

The model is designed in order to be able to also simulate both the tensile test and the bending test. For this last test, three cylindrical surfaces are included. The whole model is presented in **Figure 8**.

The first step of the simulation enables to analyze the

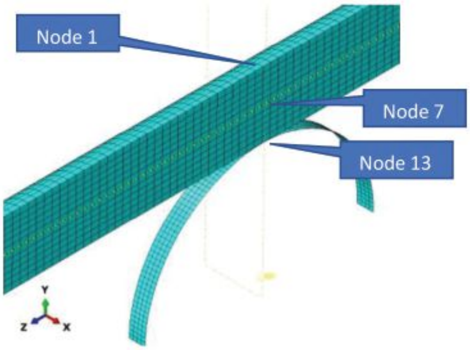

Figure 7a: Mesh of the wire.

Stress (MPa)	Plastic strain	Young Modulus (GPa)	Poisson coefficient
1000	0	165	0,28
2030	0,0072		
2070	0,0108		
2080	3		

Table 1: Material Properties.

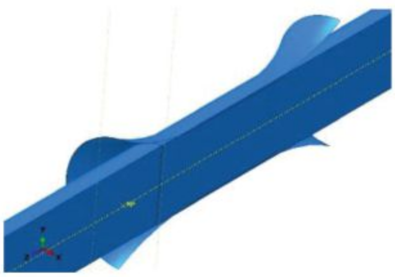

Figure 7b: Simulation of the drawing process, detail of the die.

Figure 8: Whole model to simulate drawing, tensile and bending tests.

wire state after drawing. The simulation revealed residual stress distribution after drawing, demonstrating tension at the surface and compression at the core as illustrated in **Figure 9**.

Once the wire has been drawn, the tensile test is simulated by pulling the wire at one extremity and fixing the other.

The tensile curve is defined by analyzing the evolution of the distance between two points at the surface of the wire (as done for the experiments). In order to have a detailed analysis, another similar FEA is done on a wire of 0.8 mm with the same material but without simulation of the drawing process.

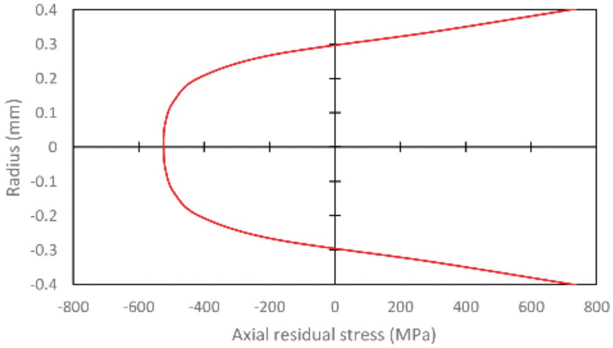

Figure 9: Axial residual stress state in the section of the wire.

The associated tensile curves are plotted in **Figure 10**. As expected, the curve without drawing perfectly fits the material data and the drawing process increases the Yield stress from 1000 to 1500 MPa. We can also note that despite the complex residual stress state (and hardening) after drawing, the linear parts of each curve are identical. This means that the tensile modulus is equal to the Young modulus: $E_t = E$.

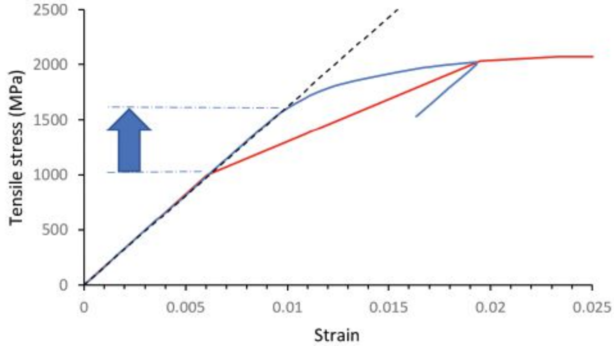

Figure 10: Simulated tensile curves without drawing (in red) and after drawing (in blue).

Then a bending test has been simulated, once again with and without drawing. The FE model is presented in **Figure 11**.

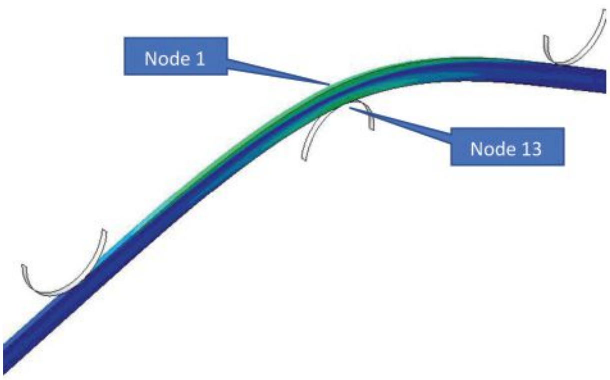

Figure 11: FE model simulating bending test.

The FE simulation enables to plot the bending curves in each case (**Figure 12**). We can clearly see that the linear rate of the curve after drawing is lower than the one without drawing.

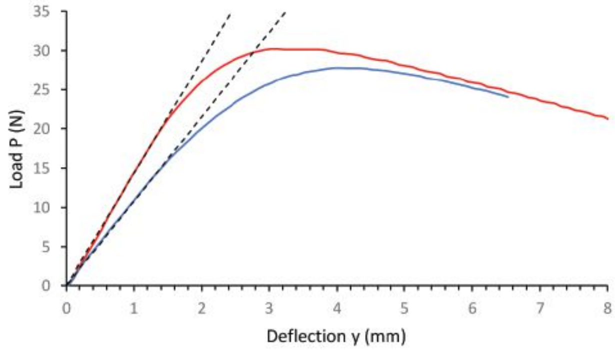

Figure 12: Simulated bending curves without drawing (in red) and after drawing (in blue).

Then Equation (1) is exploited to find the flexural modulus. As expected, the obtained flexural modulus without drawing is equal to the Young Modulus E_f= 165 GPa = E. Moreover, the flexural modulus after drawing is lower than the Young Modulus E_f = 122 GPa < E. Note than in this last case, the Young modulus entered as data for the simulation has not been modified. Nevertheless, the bending curve has a linear rate than corresponds to a lower value.

In order to explain this phenomenon, the evolution of plastic strain on a section all along the test has been plotted. The initial state after drawing is set as a reference. In a common bending test one half of the wire is in tension, the other one is in compression and the center is neutral. When the bending test begins, the wire is first in an elastic state and there is no plastic strain. Then, at a given level of external load, plastic strain appears at the external surface and progresses to the center of the wire. We can see this evolution on the upper part of **Figure 13** which is dedicated to the half of the wire in tension (positive values of plastic strain). Node 1 is at the external surface and after about 1.2 seconds of simulation time, first yielding occurs and the plastic strain progresses towards the center (node 7).

In a bending test of a material supposed to be linear elastic, homogeneous and isotropic, the behavior is the same in the compression state of the wire but it is not the case here. As shown in **Figure 13**, because of the drawing process (and thanks to the multilinear kinematic hardening simulation that considers the Bauschinger effect), early plastic strain directly appears at the beginning of the test in the part of the wire in a compression state (negative values of plastic strain). This area is highlighted by an arrow in **Figure 13** (nodes 8 to 12 are involved, except node 13 at the surface which is in a preliminary tension state due to the prestress). So, at the beginning of the test, even when the global bending behavior of the wire is linear, a part of the section is plastically deformed. We know that the material in increasing plastic state has a lower stiffness. As a consequence, the whole stiffness of the section is decreased and that explains why the calculated flexural modulus is lower than the Young modulus. From a scientific point of view, a small cold drawn wire is no more a uniform material but could be considered as a complex structure.

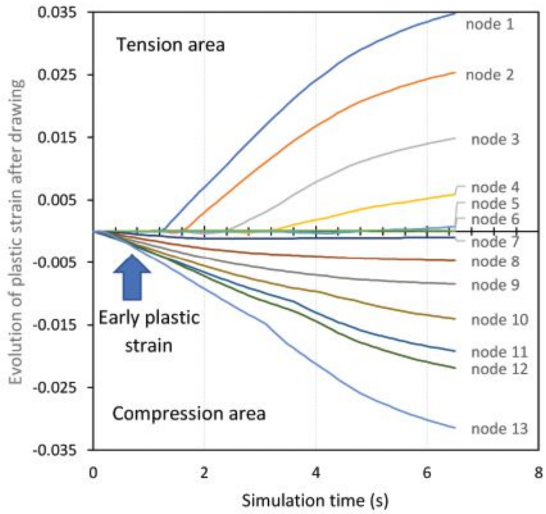

Figure 13: Evolution of plastic strain in a bending test after drawing.

Conclusion

The objective of this paper was to detail the mechanisms that are involved both in the drawing process and in bending in order to explain why the wire can be softer than expected using the Young modulus, and as a consequence, why manufacturers commonly use a dedicated flexural modulus.

A simplified Finite Element Analysis of the drawing process, with a constant Young modulus, enabled us to estimate the material state when it is delivered to manufacturers. Then the simulation continued on one case with a tensile test and on another case with a bending test. As identified by manufacturers, the wire exhibited a stiffness that corresponded to the Young modulus with the tensile test but the linear behaviour in bending was lower. A deep analysis of the simulations showed that this is due to the fact that the material was highly plastically deformed during the drawing process and that an inner part (under the surface) of the wire was directly plastically deformed in compression when the bending test begun. This amount of material under the surface that works plastically (even if the global behaviour of the wire is linear) tends to decrease the overall stiffness of the wire and induces the use of a specific elastic modulus in bending in a homogenous equivalency.

Continued...

Nomenclature:

- E: Young modulus (MPa)
- E_f: flexural modulus (MPa)
- E_t: tensile modulus (MPa)
- P/y: the slope of the linear part of the curve ($N.mm^{-1}$)
- P: radial load (N)
- y: radial deflexion (mm)
- I_y: area moment of inertia (mm^4)
- L: distance between axles in the bending test (mm)
- D: wire diameter (mm)

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