Influence of density on the electrical behaviour of a steel metallic wool

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Abstract:

The aim of this paper is to present the influence of density on the electrical behaviour of steel metallic wool. The electrical conductivity – density curves follow a power-law relationship. The exponent of the power-law is varying from 2.5 to 3.5 with the initial density. This evolution is correlated to the variation of the exponent of the power law describing the stress-density curves.

Résumé:

Le but de ce papier est de présenter l'influence de la densité sur le comportement électrique d'une laine d'acier. Les courbes conductivité électrique – densité relative sont bien décrites par une loi puissance. L'exposant de cette loi varie entre 2.3 et 3.5 avec la densité initiale. Cette évolution est corrélée avec l'exposant des lois puissances décrivant les courbes contrainte – densité.

Key-words: Metallic entangled material, mechanical properties, electrical properties

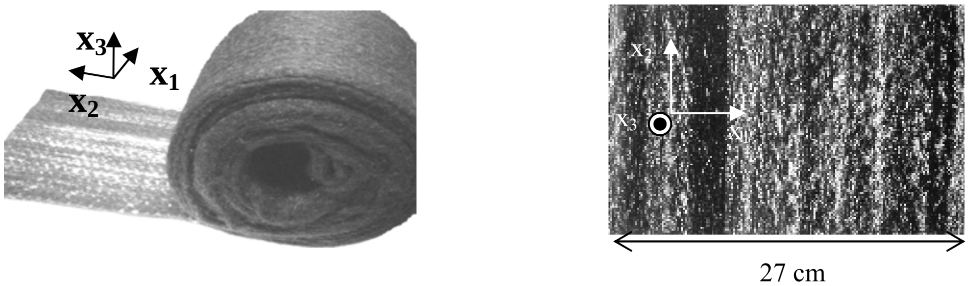
1 Introduction

Entangled materials exist from natural material (mutton wool, cotton) as well as artificial one (steel wool, glass wool, felts …). They find applications in thermal insulation, mechanical reinforcement and filtration. This kind of material is close to a cellular material in regard to its low density and discrete architecture. The knowledge about metal foams is well developed both from experimental and modelling view point (Ashby et al (2000), Gibson et al (1999)). Comparatively entangled materials have been much less investigated. Metallic wools, sintered in order to create permanent cross-links between the fibres, have been considered (Delince et al (2004), Markaki et al (2003)). In the case of non sintered entangled materials, compression experiments have been performed on several type of materials, natural (such as animal wool and human hair), and synthetic (such as carbon nanotubes), with electrical measurements during the compression (Poquillon et al (2005). Model materials (regular Nylon and steel fibres) were also tested (Poquillon et al (2006)) in order to compare with existing model. Models to understand the mechanical behaviour of fibrous material have been proposed (Van Wyk (1946), Toll (1998), Baudequin et al (1999): essentially based on dimension analysis, they establish a power-law relationship between stress and fibre volume fraction during the compression test. Recently, this scaling law has been confirmed by discrete 3D simulations (Rodney et al (2005)). Durville (2005) performed some numerical simulations confirming some proposed models.

A lot of studies around the percolation threshold are lead but fewer for large fibre volume fraction far from percolation threshold. The purpose of the present work is to study the electrical behaviour of a non-sintered steel wool with very low volume fraction of fibre (less than 2%). We will focus on the influence of the initial fibre volume fraction on the electrical conductivity-density curve during compression tests and experiments will be compared to the mechanical behaviour.

2 Material

FIG. 1 shows an example of the metallic wool considered here, along with the notation for the principal axis used throughout this article. Note in particular that direction x_2 is the rolling direction. The metallic wool is provided in form of strip (5 mm in thickness and 27 cm wide) and is made of stainless steel AISI 434 fibres. The cohesion of the material is only due to the fibres tangle. The global surface mass of the wool is 1 kg/m², which corresponds to an average fibre volume fraction, of 2% approximately. As shown in FIG. 1 b), the material is clearly anisotropic and reveals parallel bands of homogeneous density in x_2 direction. As describe in Masse et Al (2006), the fibres have an aspect ration of about 400, and samples of 30 mm by 30 mm can be extracted of homogeneous surface mass, ranging from 0.6 to 1.4 kg/m².



a) b)

FIG. 1 – Overview of the metallic wool
a) macrospcopic view with principal directions
b) centimetric view the band is 10 cm in height along the x_2 direction.

3 Experimental

In situ conductivity measurements during compression test along x_3 were performed. Samples of 30 mm by 30 mm and homogeneous surface mass were compressed between two plates without any lubrication using a 20 kN cell load. All tests were performed under a constant strain rate of 0.01 s^{-1}. The nominal stress (σ)-true strain (ε) curves and nominal stress-density (ρ) curves were extracted from the compression test, according to the following relations:

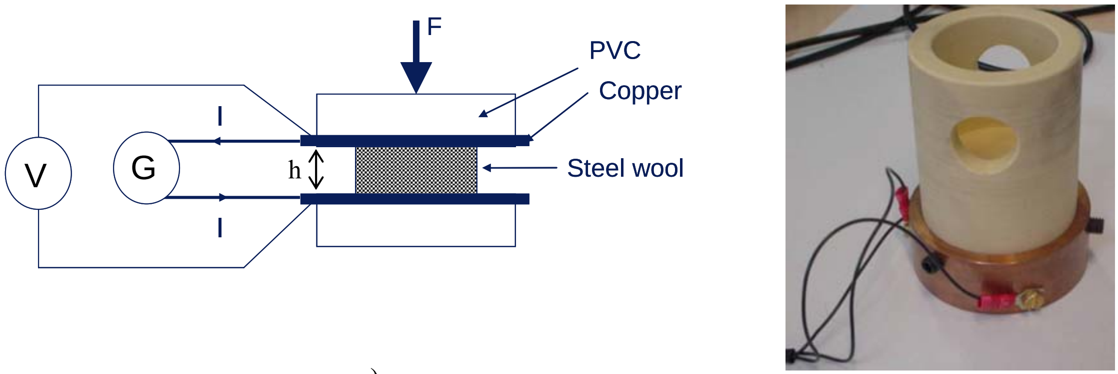
$$\sigma = \frac{F}{S_0} \quad \text{and} \quad \rho = \rho_0 \exp(-\varepsilon) \quad \text{with} \quad \varepsilon = \ln\left(\frac{h}{h_0}\right)$$

Where h_0 is the initial height of the sample, h is the height between the plates during the compression test and ρ_0 the initial density of samples. S_0, the surface of the sample, is constant during the compression test. As shown in FIG. 2 the plates were adapted for the conductivity measurements. They were constituted of PVC (isolating material) for the part in contact with the compression device and copper (conducting material) for the parts in contact with the wool. This latter part was connected to an electrical measurement device through a four-wire set up. The measurement is uninterrupted during the compression, the sampling rate is 150 ms. The resistance (R) is directly obtained and the electrical conductivity (σ*) is deduced according to the expression:

$$\sigma^* = \frac{h}{R\, S_0}$$

Thanks to these in situ measurements electrical conductivity, stress, and density were obtained simultaneously.

In order to calculate the real electrical conductivity of the wool, the resistance of the plates have to be withdrawn to the total measured resistance. This resistance was measured thanks to a plate versus plate test. The device's resistance is 0.0014 Ohm that implies $R = R_{measured} - 0.0014$.



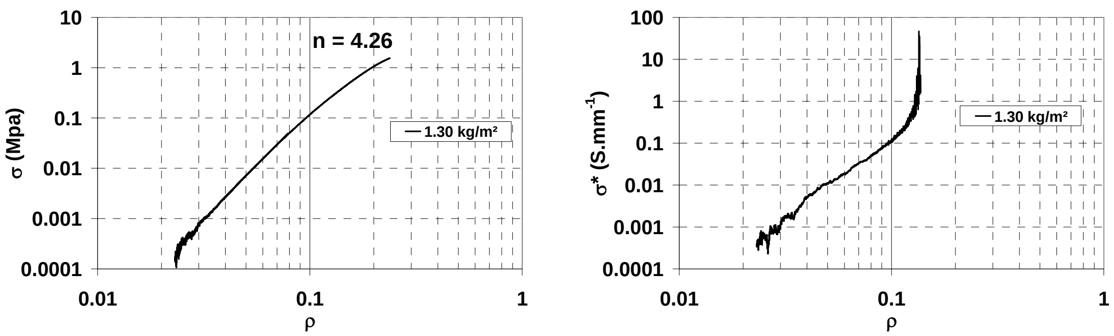
a) b)

FIG. 2 – Overview of the in situ conductivity measurement compression test a) schema of the measurement device and b) one of the plates used for the measures

Compression test without unloads were performed for different samples with surface mass ranging between 0.6 and 1.4 kg/m².

4 Results

FIG. 3 shows the mechanical stress – density curve (FIG. 3 a)) and the electrical conductivity – density curve (FIG. 3 b)), in a log-log scale, for a sample of initial surface mass of 1.30 kg/m².



a) b)

FIG. 3 – Typical experimental curves for a sample of surface mass 1.30 kg/m²:
a) nominal stress-fibre volume fraction curves
b) electrical conductivity-fibre volume fraction curves

4.1 Mechanical curves

The stress and the fibre volume fraction follow a power law relationship (FIG. 3 a)). For the range of surface mass test, this fit is valid for a fibre volume fraction ranging between 0.02 (approximately the density at the beginning of the compression) and 0.1. This result can be compared to a model proposed by Toll (Toll (1998)), which gives:

$$\sigma = kE_f(\rho^n - \rho_c^n)$$

The factor k is a single adjustable parameter of the model and accounts for orientation distribution and degree of crimp, as well as the constraints and loading direction of the fibre segments. E_f is the fibre's Young's modulus. The exponent n is a function of the wool structure: n = 3 for a random 3D structure (Van Wyk (1946)) and n = 5 for random 2D plane structure (Toll (1998)). ρ_c is the threshold volume fraction below which the wool has no mechanical response. A variation of the exponent with the surface mass of the wool was observed for this kind of steel wool (Masse et Al (2006)) and it was associated to structure variation. An exponent closed to 3 was measured for samples of low initial surface mass, which present a "more 3D" structure than samples of high surface mass which present a more 2D oriented structure and thus a higher exponent which value is 4.5. This result is shown in FIG. 4 a). This exponent is the same for the power law relationship governing the evolution of the unloads modulus in function of the fibre volume fraction during compression.

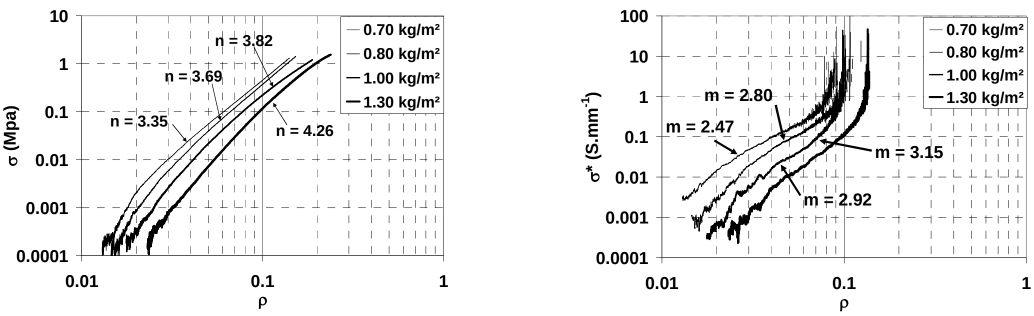
4.2 Electrical curves

The electrical curves (FIG. 3 b)) can be divided into three domains. The first one exists for fibre volume fraction ranging between the initial density and 0.04 which corresponds to an electrical conductivity of 0.01 $S.mm^{-1}$ and a mechanical stress of 0.05 MPa. This domain corresponds to the stage during which the dangling fibres of the free surface establish electrical contacts with the copper plates. A new threshold volume fraction can be determined. It can be defined as the density below which no conductivity is measured. This electrical threshold density seems to be close to the mechanical threshold density (this observation must be checked by further experiments).

The fibre volume fraction at the end of the second domain is 0.1, which corresponds to an electrical conductivity 0.1 $S.mm^{-1}$ and a mechanical stress of 0.1 MPa. This domain exhibits a quasi linear dependence of the electrical conductivity and the fibre volume fraction in a log-log scale. It seems that they are related by a power law relationship.

The third domain corresponds to saturation of R value in value of the same order of the noise of the measurement device. This domain is not considered.

The limits of these domains depend on the surface mass (FIG. 4 b)).



a) b)

FIG. 4 –Typical experimental curves for samples of different surface mass
a) nominal stress-fibre volume fraction curves
b) electrical conductivity-fibre volume fraction curves

5 Discussion

FIG. 4 shows mechanical and electrical curves for 4 different surface mass. Firstly for the same fibre volume fraction the sample with the smallest surface mass is the most conducting and the most mechanical resistant. This difference of behaviour can be explained while considering the variation of the structure when the surface mass increases. Indeed for high surface mass the structure of the wool is 2D oriented and for small surface mass the wool is more 3D like. For 3D structure, paths of fibres for electricity transport between plates are more direct than for 2D structures. Thus we can understand that the electrical conductivity is higher for the smallest surface mass at fibre volume fraction fixed.

Secondly, in the second domain of the electrical curves, the electrical conductivity seems to follow a power-law relationship with the fibre volume fraction with an exponent m ranging between 2.5 and 3.5 and increasing when the surface mass increases (FIG. 4 b)). This kind of exponent variation is similar to the one observed for the mechanical curves. Therefore a direct link between the stress and the conductivity of the wool has to be established.

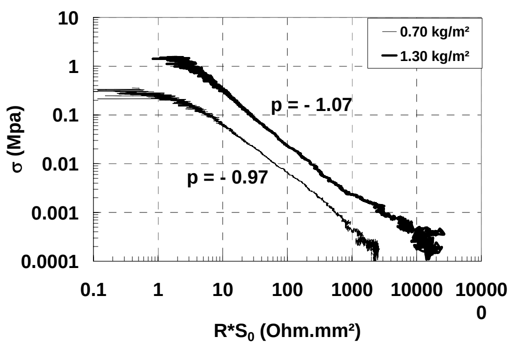


FIG. 5 – Mechanical stress-product $R*S_0$ curves for samples of surface mass 0.70 kg.m² and 1.30 kg/m²

FIG. 5 shows the mechanical stress versus the product $R*S_0$ in a log-log scale. It appears that the stress is inversely proportional to the product $R*S_0$ in a range of stress from 0.005 to 0.1 MPa, which corresponds to the limits of the domain defined previously, and included in the domain of validity of the Toll's model. FIG. 5 shows:

$$\sigma \propto \frac{1}{RS_0}$$

From this result and the definition of the electrical conductivity, we deduce:

$$\sigma^* \propto h\,\sigma = h_0 \frac{\rho_0}{\rho} \sigma$$

Considering that the threshold fibre volume fraction is negligible compared to the fibre volume fraction in the considered domain the expression of Toll's model become:

$$\sigma \propto kE_f \rho^n \quad \text{and then} \quad \sigma^* \propto h_0 \rho_0 k E_f \rho^{n-1}$$

From this expression we conclude that, experimentally, the electrical conductivity and the fibre volume fraction follow a power law relationship.

$$\sigma^* \propto \rho^m$$

The exponent of this power law relationship is connected with the exponent found for the mechanical stress by the relation: $m = n - 1$

This result could be compared to the results for open-cell foams for which the exponent of the power law relationship between the unloads modulus and relative density is 2, and the one for the power law relationship between the thermal conductivity (considering only conduction) and relative density is 1. (Gibson et Al (1999))

5 Conclusions

We studied the electrical behaviour during compression along the thickness of metallic entangled materials with surface mass ranging from 0.6 to 1.4 kg/m².

A special measurement device was developed to measure the resistance of the materials.

The electrical conductivity – density curves can be describes by three domains:

- A first domain during which the wool comes in contact with the plates, characterized by a curve with noise. This domain ends up for an electrical conductivity of 0.01 $S.mm^{-1}$.
- A second domain during which we observed a power law relationship between the electrical conductivity and the density
- A third domain during which the measured resistance is in the noise of the measurement device.

The exponent m of the electrical-density power law, observed in the second domain, is experimentally connect with the exponent n of the stress-density power-law, previously determined by the relation : $m = n - 1$.

This experimental study allows us to propose a close relation between the electrical properties and the mechanical properties, which depends of the initial structure of the material.

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