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## Microstructure-based behavior law for globular pearlitic steels

S. ALLAIN<sup>1,2\*</sup>, A. ROTH<sup>3</sup>, O. BOUAZIZ<sup>2,4</sup>, E. D'ERAMO<sup>3</sup>

<sup>1</sup> Institut Jean Lamour, UMR Université de Lorraine- CNRS 7198, Nancy, France

<sup>2</sup> Laboratory of Excellence DAMAS, Université de Lorraine, France

<sup>3</sup> Ascometal - CREAS, Hagondange, France

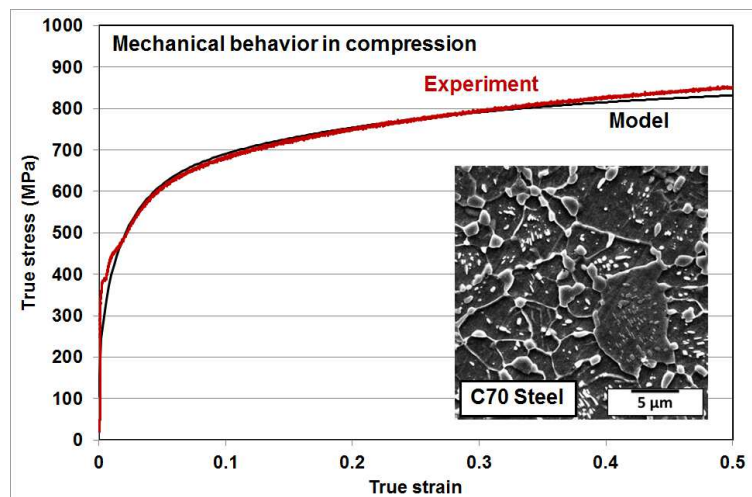
<sup>4</sup> LEM3, UMR Université de Lorraine- CNRS-ENSAM 7239, Metz, France

\* Corresponding author : [sebastien.allain@univ-lorraine.fr](mailto:sebastien.allain@univ-lorraine.fr), Institut Jean Lamour, Campus ARTEM, Allée Guinier, 54000 Nancy, France, ++33 3 72742 726

### Abstract

Pearlitic steels are widely used in the industry for their good balance between strength, ductility and machinability. Sometimes, the classical lamellar structure can degenerate in a so-called globular structure which may significantly affect the behavior of the steel. To our knowledge, no size sensitive model is available in the literature to predict their mechanical behaviors and work-hardening. Inspired by their analogy with ferrite-martensite dual-phase microstructures, we propose a new microstructure-based law for globular pearlite. It describes the evolution of the dislocation density into ferritic grains which is enhanced by the presence of hard particles. The model is as a consequence sensitive to ferritic grain but also coarse carbide sizes after globularization. The model has been calibrated on a conventional steel grade and appears to be a practical tool for microstructure design.

### Graphical abstract



### keywords

steel, pearlite, behavior, carbide, grain size

## 1. Introduction

In automotive building and general industry sector, many forged components such as crankshafts and connecting rods show a ferrite-pearlite microstructure obtained without thermal treatment after forging [1] with varying ferrite ratio depending on the required mechanical properties. Some forged connecting rods show a fully pearlitic microstructure. This particular microstructure can be obtained in low alloyed steels whose chemical compositions are close to the eutectic (commercial C70S6 steel for instance). It presents an interesting combination between **strength (ultimate tensile strength or yield strength)**, ductility (**fracture strain**) and machinability (**drilling or turning for instance**). In most cases, the pearlite microstructure show a lamellar structure inherited from the fast eutectic transformation process at high temperature, i.e. an alternation of ferrite and cementite lamellae, which dominates the mechanical properties of pearlitic steel [2]. The typical inter lamellar spacing  $s$  depends on the composition and the applied cooling rate but is generally between 100 and 300 nm. This is also the morphology of pearlite encountered in semi-products dedicated to cold-rolling and annealing in the flat product sector [3].

## 2. Behavior of pearlitic steels

It is now well admitted that the yield strength of lamellar pearlite depends on the inverse of its inter-lamellar spacing [4,5]. Its plastic behavior is governed by the mobility of dislocations in ferrite channels which are bent in between cementite lamellae. On this basis, Bouaziz et al. [6] have established a microstructure-based behavior law (flow stress  $\sigma$  as a function of the plastic strain  $\epsilon$ ) for lamellar pearlite, which can be written as follows:

$$\sigma(\epsilon) = \sigma_0 + \frac{M\mu b}{s} + \left( \frac{K}{g} \cdot \left( 1 - \exp\left(\frac{g}{2}\epsilon\right) \right) \right) \quad (1)$$

with  $g$  and  $K$  two calibrating parameters describing the work-hardening of the steel according to a Voce-type approach. These parameters surprisingly do not depend on the interlamellar spacing  $s$  and on chemical composition and seems universal whatever the studied lamellar pearlite [6].  $M$  is a Taylor factor, generally taken equal to 3.0,  $\mu$  is the shear modulus at room temperature, taken equal to 77 GPa,  $b$  the Burger's vector of mobile dislocations ( $2.5 \times 10^{-10}$  m) and  $\sigma_0$  is a friction stress comprising the lattice strength and the solid solution hardening due to substitutional alloying elements in ferrite.

Nevertheless, if the fully lamellar pearlitic steels undergo subsequent severe thermal post-treatments or are not cooled down sufficiently rapidly after pearlitic transformation, the lamellar structure can degenerate in a so-called globular structure. The evolution of cementite comprises generally three steps [7-9]: the first process is the fragmentation of cementite particle followed by the spheroidization of lamellae fragments and a coarsening process. Under such conditions, coarse cementite carbides grow rapidly at former austenite grain boundaries at the expense of intra-grain carbides whose density decreases rapidly. The driving force of all these processes is related to the decrease in the density of surface energy. In parallel, ferritic matrix can recrystallize or recover and shows in general well defined grain sizes after ripening. The Figure 1 shows a fully lamellar microstructure obtained with

a C70 steel (rapid cooling after annealing at 840°C) and the corresponding globular microstructure after a severe tempering (at 680°C during 20h) and thus after a severe globularization of the microstructure. In both cases, the ferrite appears in dark contrast whereas cementite is in bright contrast. The micrographs have been obtained by SEM after nital etching. The interlamellar spacing  $s$  of lamellar structure is 206 nm while the ferritic grain size  $d$  of the globular structure is 7  $\mu\text{m}$  and the mean size of coarse carbides  $d_m$  is 1.3  $\mu\text{m}$ .

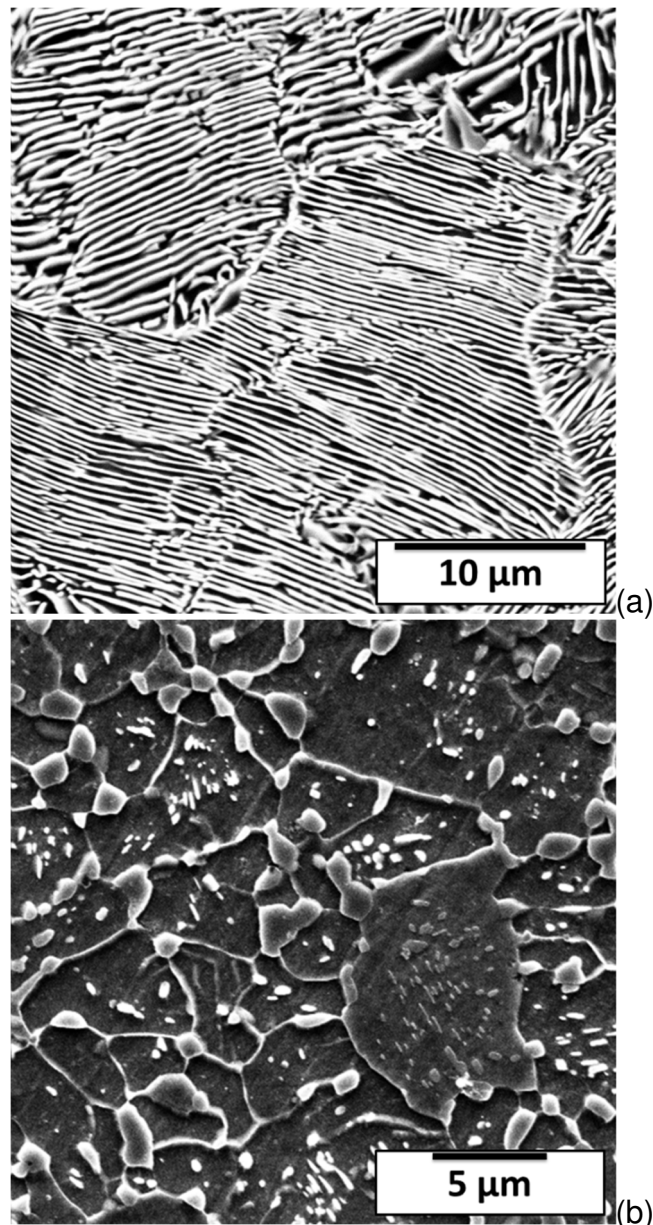


Figure 1: SEM micrographs after nital etching of a C70 steel with (a) a fully lamellar ( $s = 206 \text{ nm}$ ) and (b) a globular microstructure ( $d = 7 \mu\text{m}$ ,  $d_m = 1.3 \mu\text{m}$ ) respectively.

The globular microstructures have been obtained after a severe tempering of the lamellar microstructure (rapid cooling from 840°C followed by an annealing at 680°C during 20h).

Figure 2 shows the true mechanical behaviors of the C70 steels shown in Figure 1, with the lamellar and globular microstructures respectively. These curves have been obtained by compressive tests using a Gleeble 3500 machine at room temperature

and at low strain rate ( $10^{-3} \text{ s}^{-1}$ ). As expected, globular pearlitic steel show far lower strength than lamellar one despite the same fraction of cementite (in both cases close to the equilibrium,  $F_m = 12\%$ ). The mechanisms hindering the mobility of dislocations are thus obviously not the same.

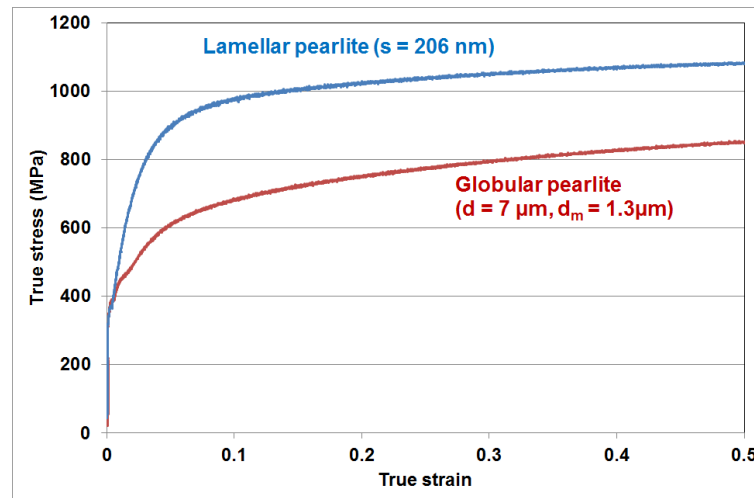


Figure 2: True behaviors of lamellar and globular pearlitic steels shown in Figure 2 measured in compression using a Gleeble 3500 at room temperature and at low strain rate ( $10^{-3} \text{ s}^{-1}$ ).

### 3. Modeling and calibration

After globularisation, the Ferrite-Cementite microstructure is closer to a composite structure as observed in Ferrite-Martensite Dual-Phase (DP) steels, the coarse cementite islands playing the role of martensite islands. Taupin et al. [10] have studied the hardening produced by such coarse cementite particles and have investigated how strain-gradients develop around particles and cause a size-sensitive extra-hardening in ferrite. They hence prove that the hardening mechanisms are in fact similar to the one reported in DP steels [11]. Unfortunately, their approach does not consider the ferrite grain and requires generalized self-consistent scheme to solve the multi-layer composite structures.

Based on this similarity with DP steels, we have investigated the possibility to use a microstructure-based behavior law for DP steels to predict the mechanical properties of globular pearlitic steel. As explained in [11], three families of approaches for DP steels have been developed in the literature: mean field monophasic models [12,13], composite models [11,14] and local-field approaches [15-18]. The two latter kinds are suitable for DP steels with high fraction of martensite in which martensite is supposed to deform plastically. As the fraction of hard reinforcing particles  $F_m$  is limited in globular pearlite, a monophasic approach in which the macroscopic behavior is modeled considering only the ferritic matrix affected by the presence of hard particles is preferable.

Based on this analysis, we have considered in this work the model proposed by [12] for DP steels containing low fraction of martensite. For more details, please refer to this original work. The proposed behavior law comprises three contributions. The first one is derived from a simplified Mecking-Kocks-Estrin (MKE) approach to describe the work-hardening of the ferritic matrix alone. The flow stress is governed by the forest hardening in ferrite which increases when the density of statistically stored dislocations in ferrite grain increases with plastic strain. This contribution is sensitive

to the ferritic grain size ( $d$ ). The second contribution is derived from the seminal work of Ashby [19] and describes an additional dislocation density in ferrite due to the strain incompatibility between cementite and ferrite. The third contribution is finally due to the load transfer between the soft and hard phases. This last contribution to work-hardening is inspired from the Brown-Stobbs-Atkinson's work [20,21] and is essentially of kinematical nature, contrary to the two previous isotropic contributions. Finally, we propose to model the behavior of globular pearlite as follows:

$$\sigma(\epsilon) = \sigma_0 + \alpha M \mu \sqrt{b} \sqrt{\frac{1 - \exp(-fM\epsilon)}{f d}} + 8 \frac{F_m}{d_m} \frac{1 - \exp(-rM\epsilon)}{r} + M \mu \sqrt{b} \frac{F_m}{\sqrt{d_m}} \sqrt{\frac{1 - \exp(-r'M\epsilon)}{r'}} \quad (2)$$

with  $\alpha$  a parameter describing the resistance of forest dislocations (taken equal to 0.3),  $f$  a parameter describing the dynamic recovery in the MKE approach for ferritic steels (set to 1.2, a value close to the one reported as in [11]) and  $r$  and  $r'$  two parameters describing the saturation of isotropic and kinematical hardening due to hard cementite particles respectively.  $r$  and  $r'$  values must be set to 6.0 to describe the behavior of DP steels [11,12]. These parameters have however been reassessed in the present study as the extension of plastic strain-gradients and the associated accumulation of geometrically necessary dislocations is different around cementite particles and martensite islands.

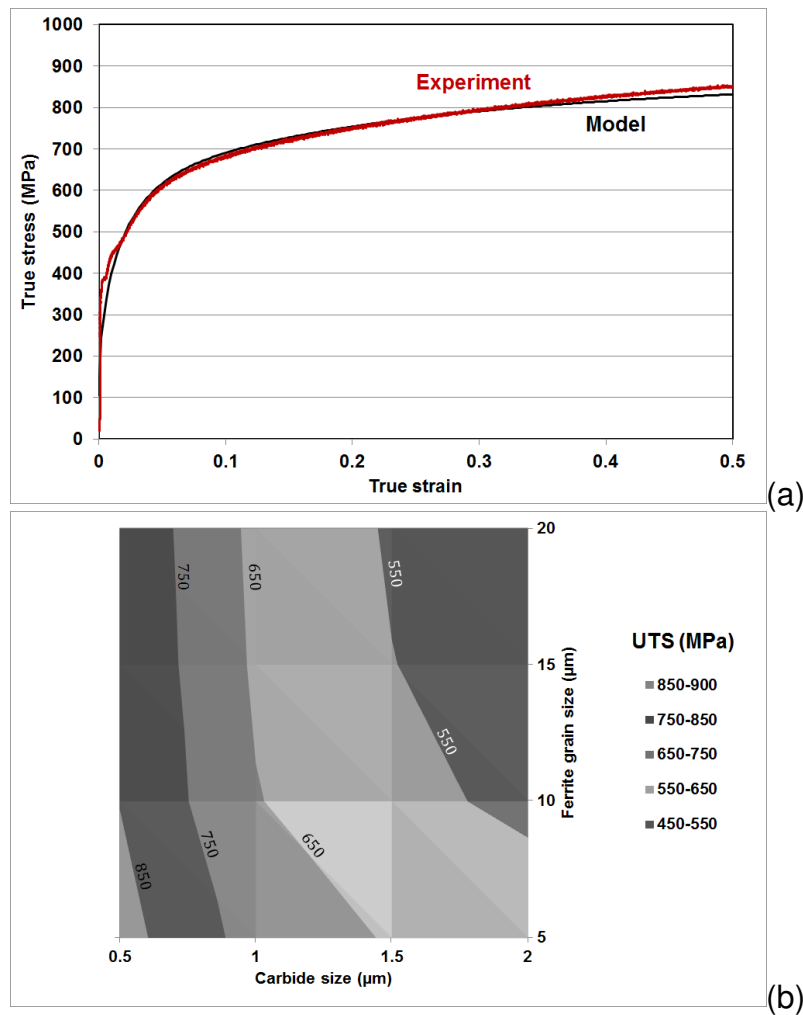


Figure 3: (a) Comparison between the experimental (red) and simulated (black) behavior curves of globular microstructures (C70 steel) (b) Calculated UTS maps of steels described using equation (2) obtained by varying  $d$  and  $d_m$ .

To do so, the prediction of equation 2 has been compared to the experimental behavior law presented in Figure 2. The ferritic grain size  $d$  has been set to  $7\ \mu\text{m}$ , the fraction  $F_m$  of hard particles to 12% and their sizes to  $1.3\ \mu\text{m}$ .  $r$  and  $r'$  have then been calibrated to reach a satisfactory agreement between experiment and modeling as shown in Figure 3a. ( $r = r' = 12.0$ ). Once adjusted, the behavior law enables capturing nicely the experimental work-hardening rate as well as the yield strength and flow stress at high strain (up to 50%).

#### 4. Discussion and conclusions

Beyond the prediction of the behavior of steels, equation (2) represents a practical tool for microstructure design. The Figure 3b shows for instance the calculated Ultimate Tensile Strength (UTS) of globular pearlitic steels as a function of carbide sizes and ferritic grain sizes, while keeping the same chemical composition (constant  $\sigma_0$  and  $F_m$ ). The Considere's criterion has been used to determine the UTS for each calculated behavior curve. In the studied domain of sizes, it appears for instance that the decrease in strength due to carbide coarsening can be moderate for very fine grained structures. Providing that it is possible to deconvolute ferrite grain recrystallization and growth from carbide coarsening, it offers unique possibilities to optimize the properties of globular steels during normalizing processes.

As a conclusion, it has been established that the microstructure-based behavior law by Bouaziz for Dual-Phase steels can thus be used to model globular pearlite, considering that coarse cementite particles act as fine martensite islands and providing some minor adjustments of calibration parameters. The calibration parameters have been reassessed to take into account the specificities of ferrite-cementite steels. This law is finally shown to be a practical tool for microstructure design.

Declarations of interest  
none

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