EVALUATION OF NUMERICAL CHARACTERISTICS OF TRUE INTERLAMELLAR SPACING OF PEARLITE IN EUTECTOID STEEL AFTER COLD WIRE DRAWING

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Abstract

Alloys that have lamellar structures, e.g., pearlitic steel, are widely used in practice. Nowadays, perlitic steel wires for tyre cords, springs and ropes are studied extensively at our laboratory of wire drawing. In the metallographic analysis of pearlite, the interlamellar spacings observed are not true spacings because the lamellae usually are not oriented perpendicular to the observation planes. The measured interlamellar spacing is called apparent. Evaluation of true interlamellar spacing from microstructural observations is based on the assumption of a uniform distribution of the probability of the angle between lamellae and the observation plane. As the lamellae change their orientation during cold wire drawing, this assumption no longer applies. This paper deals with evaluation of numerical characteristics of true interlamellar spacing in drawn pearlitic steel wire. We analyzed wires from C78D steel for ropes upon varying degrees of deformation.

Keywords: Interlamellar spacing, pearlite, wire drawing, steel

1. INTRODUCTION

1.1. Undeformed Pearlite

Alloys that have lamellar structures, e.g., pearlitic steel, are widely used in practice. Nowadays, pearlitic steel wires for tyre cords, springs and ropes are studied extensively at our laboratory of wire drawing. The microstructure of pearlite is described using three parameters: interlamellar spacing (IS), the size of a pearlite colony and the volume fraction of cementite. The most important of these is the IS defined as the perpendicular distance across two consecutive lamellae, e.g., ferrite and cementite. In the metallographic analysis of pearlite, the IS observed is not true spacing because the lamellae usually are not oriented perpendicular to the observation plane [1, 2]. The measured IS is called apparent (see **Fig. 1**). The question then arises as to how to determine the true IS from the measured spacing values? The answer lies in mathematical statistics. We have used two assumptions: 1) the pearlite colonies in our specimen have random orientations which means that the Θ angle is a continuous random variable with a uniform probability distribution. 2) true IS λ_0 is a continuous random variable that obeys a normal (Gaussian) probability distribution. Based on the first assumption, Pellisier [3] derived an equation for the probability density function of apparent IS λ:

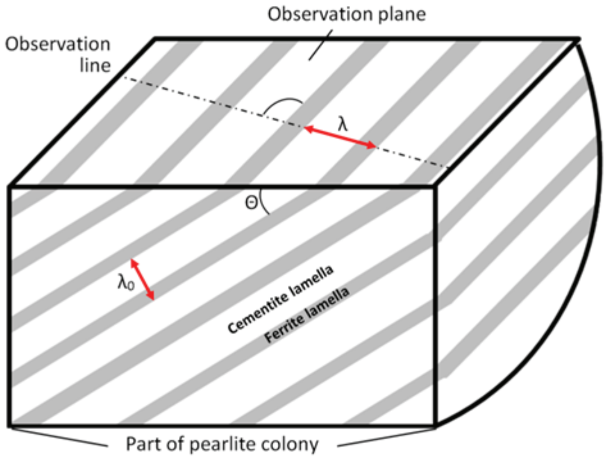

Fig. 1 Definition of the angle between a normal vector of lamellae and the observation section Θ, true interlamellar spacing λ_0 and apparent interlamellar spacing λ

$$P_\lambda = \frac{\lambda_0^2}{\lambda^2 \cdot \sqrt{\lambda^2 - \lambda_0^2}} \qquad [-] \tag{1}$$

The probability density of true IS λ_0 is given by the known expression:

$$P_{\lambda_0} = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{\frac{(\lambda_0 - \lambda_{0,Avg})}{2 \cdot \sigma^2}} \qquad [-] \tag{2}$$

where $\lambda_{0,\,Avg}$ is the average and σ is the standard deviation of true IS.

On the basis of these two equations, Ikeda [4] derived a relationship for the relative frequency F of the lamellae with apparent IS between λ_1 and λ_2:

$$F(\lambda_1, \lambda_1) = \frac{\int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^3} \cdot \left(\int_0^\lambda e^{-\frac{(\lambda_0 - \lambda_{0,Avg})^2}{2 \cdot \sigma^2}} \cdot \frac{\lambda_0^2}{\sqrt{\lambda^2 - \lambda_0^2}} \cdot d\lambda_0 \right) \cdot d\lambda}{\int_0^\infty \frac{1}{\lambda^3} \cdot \left(\int_0^\lambda e^{-\frac{(\lambda_0 - \lambda_{0,Avg})^2}{2 \cdot \sigma^2}} \cdot \frac{\lambda_0^2}{\sqrt{\lambda^2 - \lambda_0^2}} \cdot d\lambda_0 \right) \cdot d\lambda} \qquad [-] \tag{3}$$

Using this equation, we can construct a theoretical histogram of apparent IS and, by comparison with the actual histogram based on measured data, determine the $\lambda_{0,\,Avg}$ and σ values for true IS.

1.2. Deformed Pearlite

During wire drawing, IS decreases with increasing amount of strain. The deformation of pearlite occurs in three stages. In the first stage, deformation takes place in ferrite lamellae. In the second stage, cementite lamellae bend and rotate. Finally, the cementite lamellae deform and break up. These stages can be identified in the tensile strength vs. accumulated reduction diagram. In the second stage, the slope of the curve is considerably less steep than in stages 1 and 2 [5 - 7].

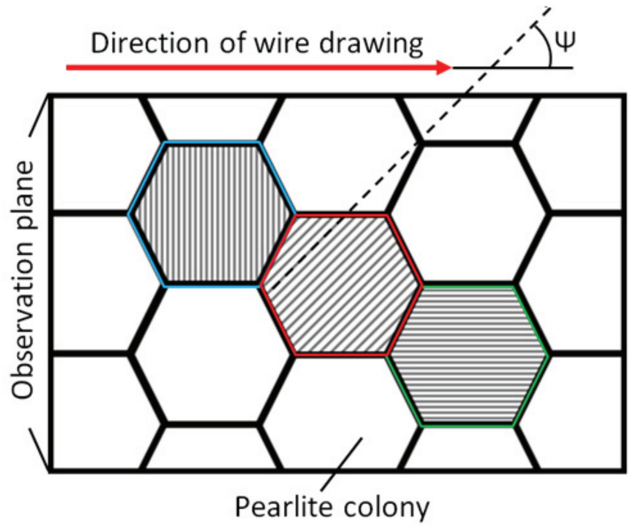

Fig. 2 Definition of the angle between lamellae and the direction of wire drawing Ψ. The sketch shows three types of spatial arrangement of pearlite lamellae: inclined (red), parallel to the wire axis (green) and perpendicular to the wire axis (blue)

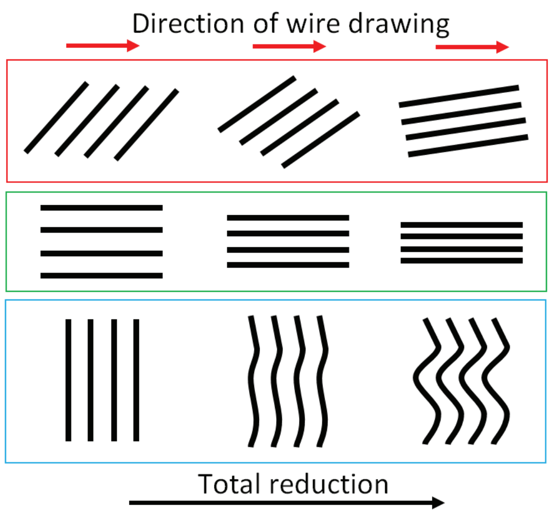

Fig. 3 A sketch of changes in lamellae orientation and IS within the three colonies from **Fig. 2**

The amount of change in IS upon the deformation process depends on the initial orientation of the lamellae, i.e. on angle Θ (provided that the observation plane is parallel to the drawing direction), as well as on angle Ψ (as defined in **Fig. 2.**). Changes in lamellae orientation and IS within the three colonies from **Fig. 2** are schematically shown in **Fig. 3**. Theoretically, the smallest resulting IS is obtained when Θ = 0° and, at the same time, Ψ = 0°. As these angles increase, the IS diminishes more slowly during deformation. At Θ = 90° and Ψ = 90°, the IS remains practically constant during the process. The lamellae bend extensively and then fracture. Some authors have reported that beyond certain amount of deformation, lamellae in all colonies became aligned to the drawing direction [8, 9]. However, this applies to true strain levels of more than $e_l = 2.5$ which are not normally encountered in practice. In our experiment which is based on practical experience, the true strain achieved is $e_l = 1.64$.

In the previous paragraph, we discussed the theory of changes in lamellae orientation and IS. In practice, their development is affected by the drawing process conditions, such as one-pass reduction, pass schedule type [10] and the coefficient of friction of the drawing die. In the experiment described in the present paper and in follow-up experiments, we discuss whether the comparison between theoretical frequencies of IS and measured frequencies can be employed to describe the effect of processing parameters on the microstructure of pearlitic steel.

2. DESCRIPTION OF EXPERIMENT

2.1. Material

The experimental material was a drawn and patented wire of 3.4 mm diameter of C78DP steel, the composition of which is given in **Table 1**. Its microstructure consisted of lamellar pearlite (see **Fig. 1**) and a small amount (up to 2 %) of upper bainite (see **Fig. 2**). The occurrence of bainite is due to out-of-standard patenting temperature. Wires of small diameters require higher lead bath temperatures which are difficult to achieve in practice. The wire was pickled and its surface was coated with lubricant carrier.

Table 1 Chemical composition of the steel examined (wg. %)

C	Mn	Si	P	S	Cu	Ni	Cr
0.79	0.63	0.20	0.010	0.014	0.04	0.02	0.05

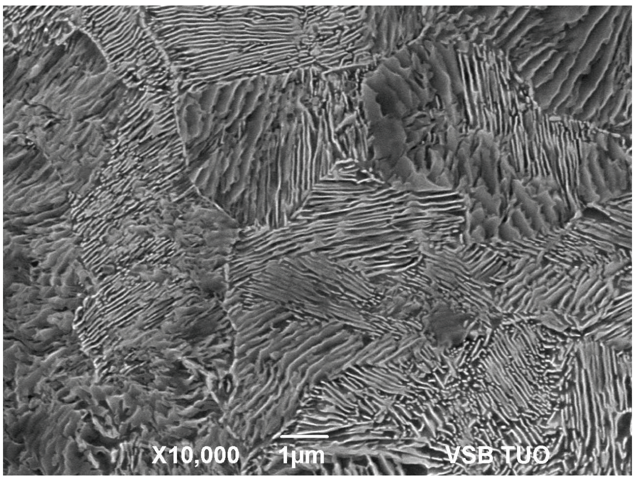

Fig. 1 Initial microstructure of the steel (SEM) - diverse orientations of lamellae with respect to the etched surface plane

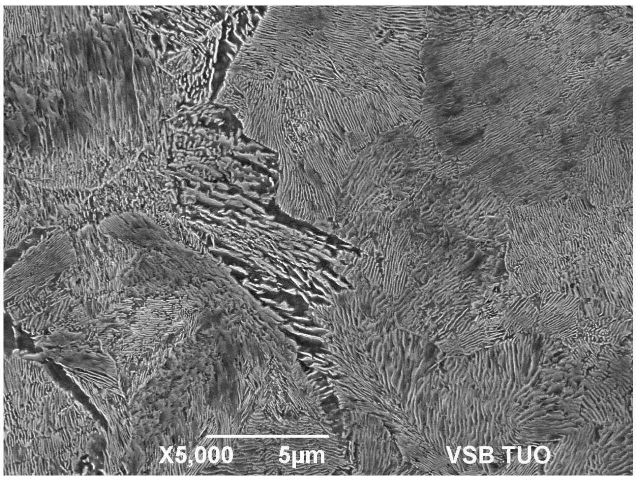

Fig. 2 Initial microstructure of the steel (SEM) - region with upper bainite

2.2. Wire Drawing

The wire was drawn from the diameter of 3.4 mm to 1.5 mm using straight-through single-block KOCH KGT 25 - E wire drawing machine with a drawing block diameter of 600 mm and a water-cooled rotating drawing die holder. The total reduction

Table 2 Drawing pass schedule

Pass number		0	1	2	3	4	5
Wire diameter	(mm)	3.4	2.9	2.45	2.1	1.75	1.5
Reduction	(%)		27.2	28.6	26.5	30.6	26.5

was 80.5 % (e_l = 1.64). The drawing speed was approximately 1 m/s. The WC drawing dies had an approach angle of 8°. The lubricant used was a commercial Condat 3T hard soap-based grade with an addition of lubricant carrier. The pass schedule used is described in **Table 2**. Following each pass, a length of wire sufficient for metallographic analysis and mechanical testing was taken from the drawn stock.

3. DISCUSSION OF RESULTS

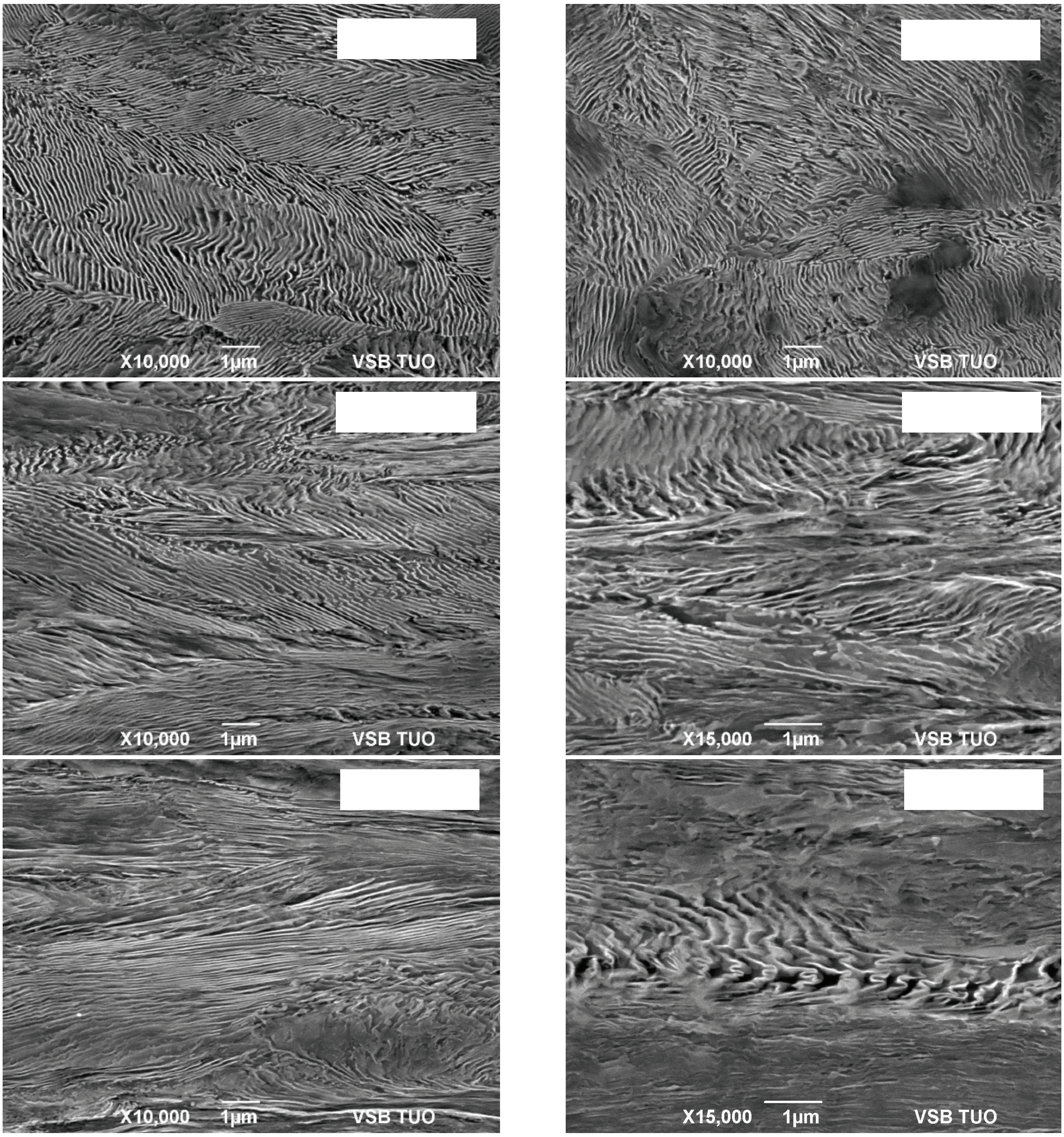

Fig. 3 Micrographs of wire upon individual passes: d_1, d_2, d_3, d_4 and d_5. The detail of the microstructure after the last pass is an example of bending of the lamellae which are perpendicular to the drawing direction

Metallographic analysis was conducted on scanning electron micrographs (SEM) of the wire axis area. A total of 10 photographs were taken on each specimen, using the magnification of 10000×. The micrographs were taken in a consecutive sequence of adjacent locations so that the selection of the area did not affect the subsequent analysis. Microstructures obtained upon individual passes are shown in **Fig. 3**. The micrographs reveal that there are substantial differences among the rates, at which IS decreases in various pearlite colonies, and that the most severe decrease in IS occurs in the last two passes.

Fig. 4 compares histograms constructed using measured data (in each specimen, between 85 and 215 colonies were measured) and theoretical frequencies calculated using equation (3). For the initial specimen of the steel, i.e. for patented microstructure, a very good agreement was found between calculated and measured data. In this case, the assumption of random orientations of pearlite colonies holds (as the red curve intersects the tops of the blue columns approximately in the middle of their width). With increasing amount of deformation, there are more and more readings that deviate from the theoretical assumptions (green areas in **Fig. 4**).

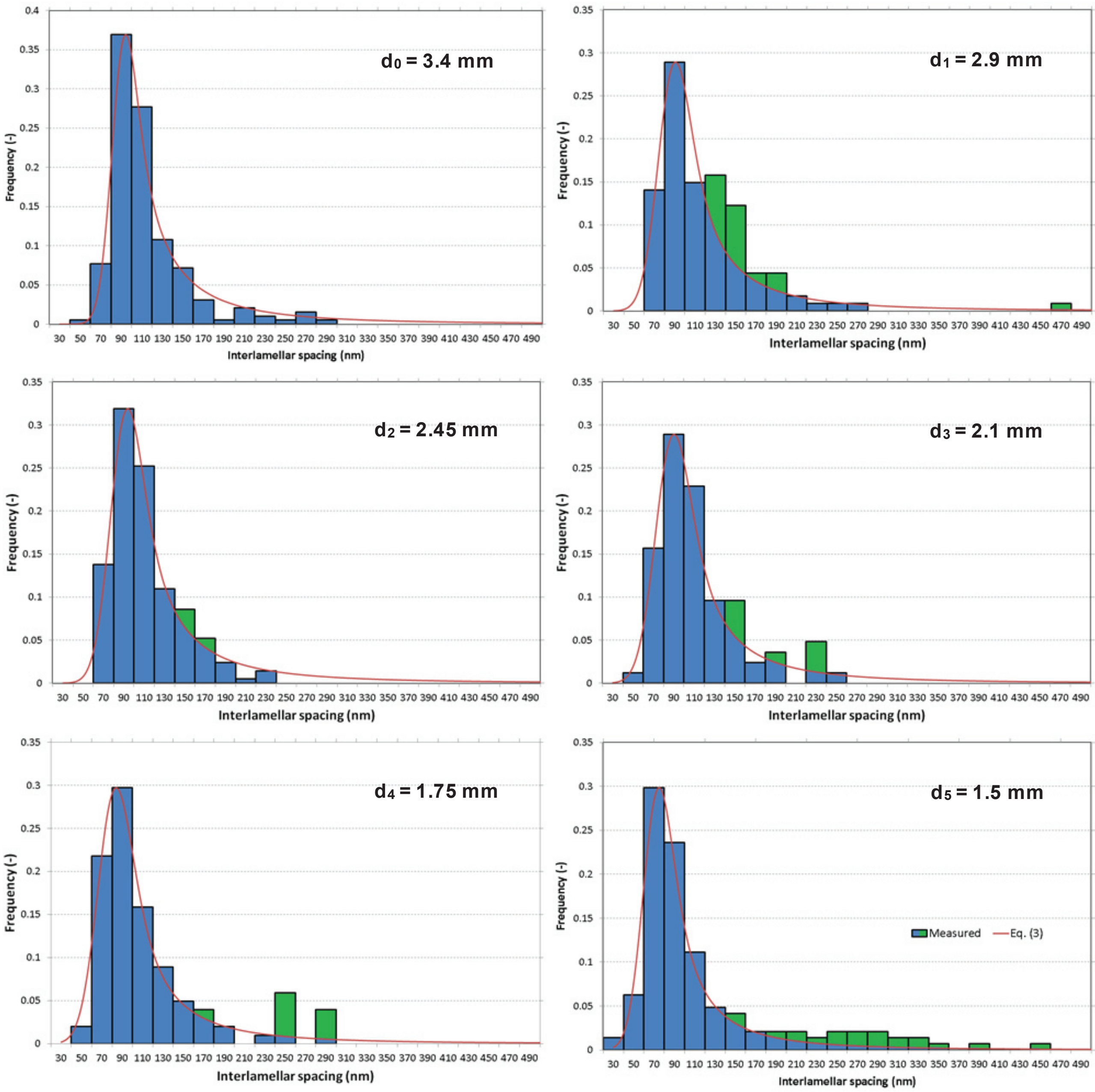

Fig. 4 Comparison between histograms constructed from measured data and theoretical relative frequences calculated using equation (3) for the initial wire diameter d_0 and wire diameters upon each of the five passes: d_1, d_2, d_3, d_4 and d_5. In the green columns, the frequencies are higher than theoretical

IS continues to diminish but the rate of decrease depends on initial orientation (i.e. the Θ and Ψ angles). Hence, there must be some amount of colonies whose orientation and IS do not change substantially, which then causes the discrepancy between the calculation according to equation (3) and the measured relative frequencies. It is these discrepancies that will help us - in the future - to describe the impact of the drawing process conditions on the microstructure of the wire.

Thanks to the above analysis, we have been able to determine the average value $\lambda_{0,\,Avg}$ and the standard deviation σ of true IS. The values are given in **Table 3** which also compares the average and the median of apparent IS. If we compare all three numerical characteristics, we find not only absolute differences between values but also variations in their response to increasing deformation. The average of apparent IS shows almost no development (the IS fluctuates around 117 nm). By contrast, the median of apparent IS has been able to reflect the decrease in IS in the last two passes. However, it is only the average true IS that reflects the development of IS across all passes. This fact stands out if we compare its values with tensile strengths after individual passes (see **Fig. 5**). **Fig. 5** shows that there is a strong correlation between IS and tensile strength. Each of the curves comprises three regions (with different slopes) reflecting different plastic deformation mechanisms operating in pearlite. **Fig. 6** shows correlation between IS (both Average of true IS and Average of apparent IS) and tensile strength.

Table 3 Numerical characteristics of IS

Pass number		0	1	2	3	4	5
Wire diameter	(mm)	3.4	2.9	2.45	2.1	1.75	1.5
Average of true IS	(nm)	86	80	77	76	70	62
Standard deviation of true IS	(nm)	12	15	15	16	16	14
Average of apparent IS	(nm)	115	112	123	115	118	121
Median of apparent IS	(nm)	104	105	114	104	99	91

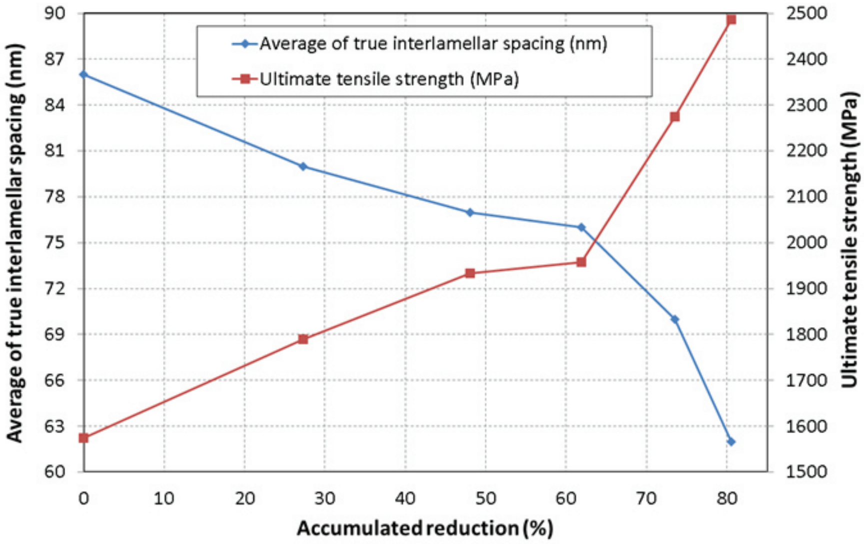

Fig. 5 Development of IS and tensile strength

4. CONCLUSION

In the present paper, we have used a specific example of drawing a wire of eutectoid steel to demonstrate the potential of evaluation of numerical characteristics of IS of pearlite. This evaluation procedure is based on the work by Ikeda [4]. Here, we compared theoretically calculated frequencies with histograms constructed from measured data. The theoretical calculation is based on the assumption that the lamellae have random orientations and that the true IS is a random variable with a normal probability distribution. As the drawing process continues, the first assumption ceases to apply. Despite that, the present method can be deployed and even provides remarkable information which can be useful in comparing various pass schedules (with different one-pass reductions and configurations e.g. - decreasing one-pass reduction vs. constant one-pass reduction schedules).

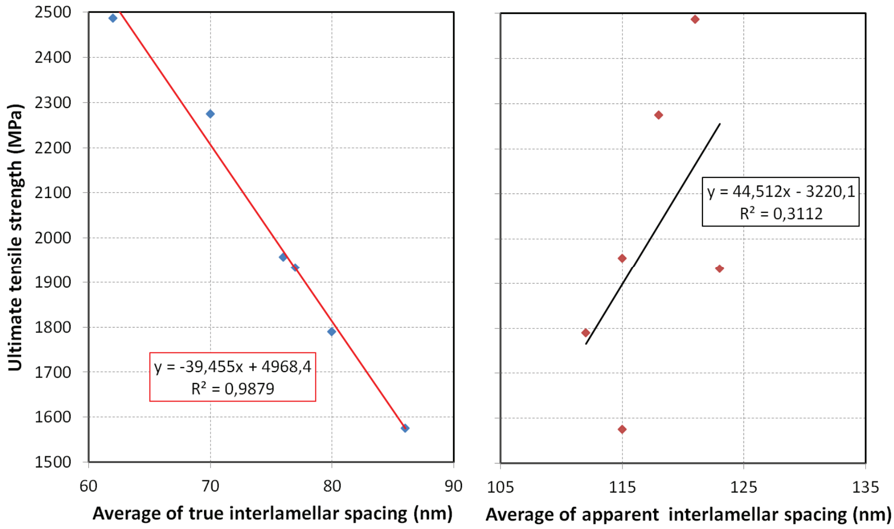

Fig. 6 Dependence of tensile strength on IS expressed by different numerical characteristics

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