Microstructure Strength Relationship of Low Carbon Martensite

W. Österle
Bundesanstalt für Materialforschung und -prüfung (BAM), D-1000 Berlin 45

Introduction

Depending mainly on carbon content and cooling rate, the following types of transformation products have been observed in iron and low carbon steel: equiaxed ferrite, massive ferrite, bainitic ferrite, lath martensite and twinned martensite. Wilson could show that all five types can occur in pure iron if only the cooling rate is high enough (1). Lowering the transformation temperature causes a transition from equiaxed to lath - or plate - like morphology. Likewise the dislocation density increases (2). Kehoe and Kelly (3) suggested to correlate the different strength levels of the transformation microstructures with their dislocation densities by means of the well known work hardening relationship:

$$\sigma_y = \sigma_0 + \alpha \; Gb \sqrt{\rho} \qquad \text{Equ. 1}$$

with σ_y: yield strength (0,2 % plastic strain), σ_0: friction stress, α: a constant of about unity, G: shear modulus, b: Burgers vector of slip dislocations and ρ: dislocation density. Equ. 1 has been proved for lath martensite in pure Fe-C alloys with carbon content 0.01 - 0.1 % C (3).

Another approach to explain the high strength of bainitic and martensitic microstructures is based on the assumption of a Hall-Petch relationship. Then an appropriate grain size has to be defined. From the review article of Kalwa et al. (4) it seems reasonable that the mean lath width is most important in respect to yield strength whereas packet size and prior austenite grain size rather determine impact properties.

Both, dislocation density and lath width, are expected to give high strength contributions in the case of bainitic or martensitc microstructures. But it is not quite clear yet how the different strengthening mechanismus have to be combined in order to be able to calculate the macroscopic yield strength from the microstructural parameters. It was the aim of this work to provide further experimental data and check possible combination laws.

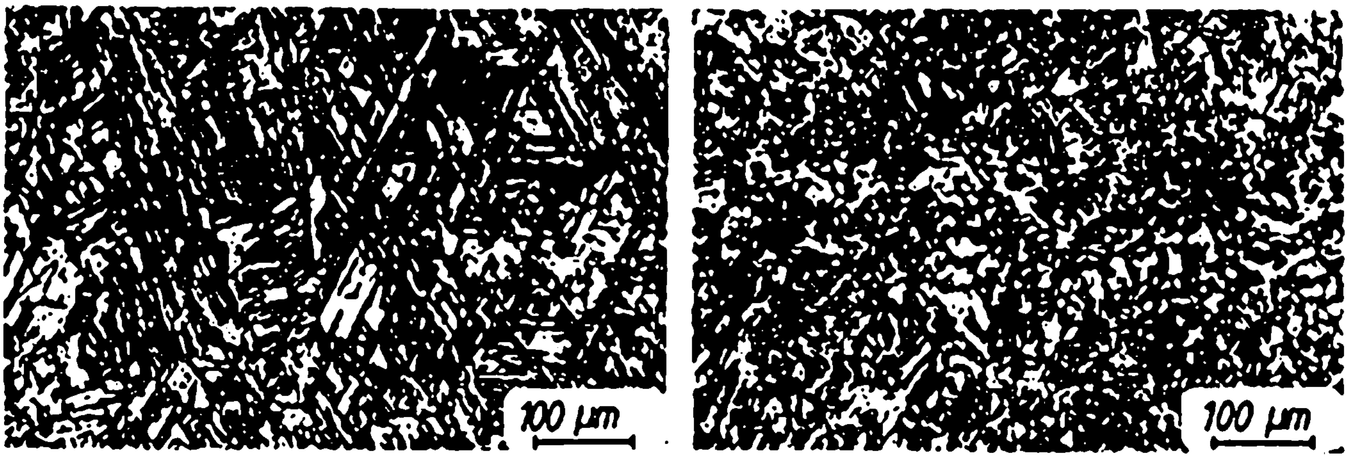
Experimental Procedure

The material used for this investigation was a microalloyed steel with the following chemical composition (mass fractions):

C	Si	Mn	P	S	Al	N	Cu	Cr	Ni	V
0.03	0.22	1.41	0.01	0.01	0.03	0.01	0.01	0.03	0.02	0.11

Specimens with the dimensions 15 x 15 x 70 (mm^3) were cut from the center of a 18 mm thick hot-rolled sheet.

During the austenitization treatment at 1300 °C the vanadium-carbonitride was completely dissolved. Quenching into water lead to a coarse martensitic microstructure as shown in Fig. 1 a). Fig. 1 b) on the other hand shows the refined microstructure which was obtained after reaustenitization at 1050 °C followed by water quench.



a) treatment A: quenched from 1300 °C b) treatment B: quenched from 1050 °C
Fig. 1: Optical micrographs, nital etch

As suggested by Naylor (5) the grain size was defined as the mean slip line length M within a lath of width w and length l:

$$M = \frac{2}{\pi} \left(w \left(\ln \left(\tan \frac{\arccos w/l}{2} + \frac{\pi}{4} \right) \right) + \frac{\pi}{2} l - l \arccos w/l \right) \qquad \text{Equ. 2}$$

Since the aspect ratio of the laths was high, l had to be measured with the optical microscope whereas w was determined with the transmission electron microscope (TEM).

Dislocation densities were measured on TEM micrographs according th Ham's intercept method (6). The foil thickness at the respective sites of evaluation were determined on appropriate convergent beam electron diffraction patterns as suggested by Kelly et al. (7).

Tensile tests were performed with cylindrical specimens of 5 mm diameter and 50 mm gauge length with a strain rate of approximately $2 \times 10^{-4}\ s^{-1}$.

Results

Fig. 2 shows the yield strengths of our tensile specimens compared to the data published by Speich and Warlimont for Fe-C alloys. The samples quenched from 1300 °C correspond quite good to the straight line found for lath martensite. The lower austenitization temperature on the other hand lead to a considerable decrease of strength. This behaviour is similar to the martensite-massive ferrite transition found by Speich and Warlimont at 0.014 % C. But in the microalloyed steel the reason for the observed drop of yield strength rather was caused by an increase of the M_s temperature as a consequence of the precipitation of vanadium carbide in the austenite thus leading to a lower carbon content in the matrix. This would result in a shift of the squares in Fig. 3 to the left, again fitting the straight line at a somewhat lower carbon content. TEM micrographs actually showed some small precipitates at dislocations after heat treatment B.

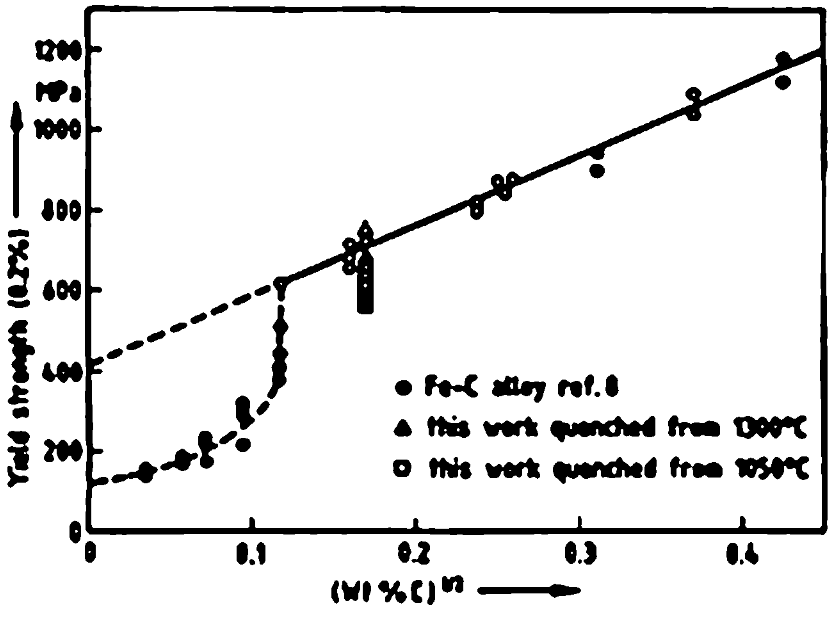
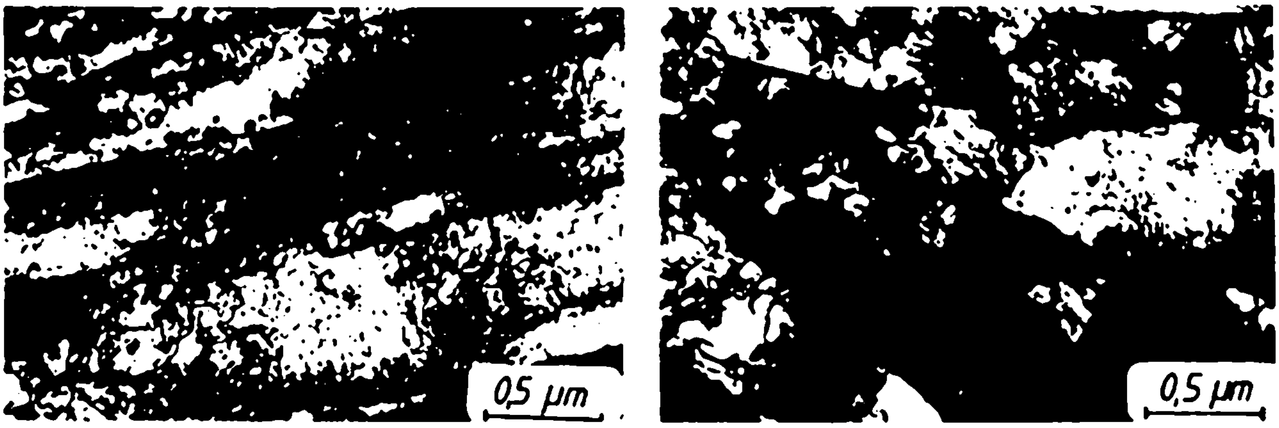


Fig. 2: Influence of carbon content on the yield strength of quenched Fe-C alloys according to ref. 8

Fig. 3 shows typical TEM micrographs of the two microstructures. The transition from lath-type to a more granular structure as well as a decrease of dislocation density is evident.

A feature common for both microstructures is shown in Fig. 4. Quite often thin sheets were observed at lath boundaries which produced extra spots in the diffraction pattern. The evaluation of different suitable orientations lead to the conclusion that these layers are twins to the adjacent lath though sometimes indexing as retained austenite or even cementite was possible as well. Similar observations were published recently by Gates et al. (9).



a) treatment A: quenched from 1300 °C b) treatment B: quenched from 1050 °C

Fig. 3: TEM micrographs

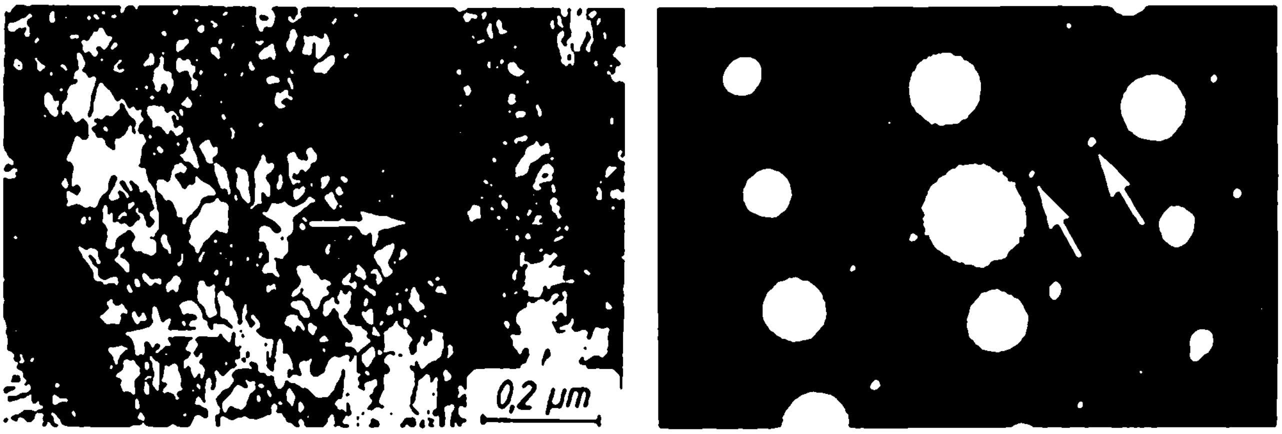


Fig. 4: Twinned layers in dark contrast and corresponding extra spots in the diffraction pattern (marked by arrows)

Quantitative measurements of lath dimensions are represented in Fig. 5. Based on these data weighted average values were obtained and an average slip line length $\bar{M}$ was calculated with Equ. 2. The results are summarized in Table 1 together with the measured dislocation densities.

Though the martensitic microstructure after treatment A appears coarse in the optical microscope (Fig. 1) the effective grain size $\bar{M}$ is even smaller than for treatment B. This points to the dominant role of the lath width in Equ. 2.

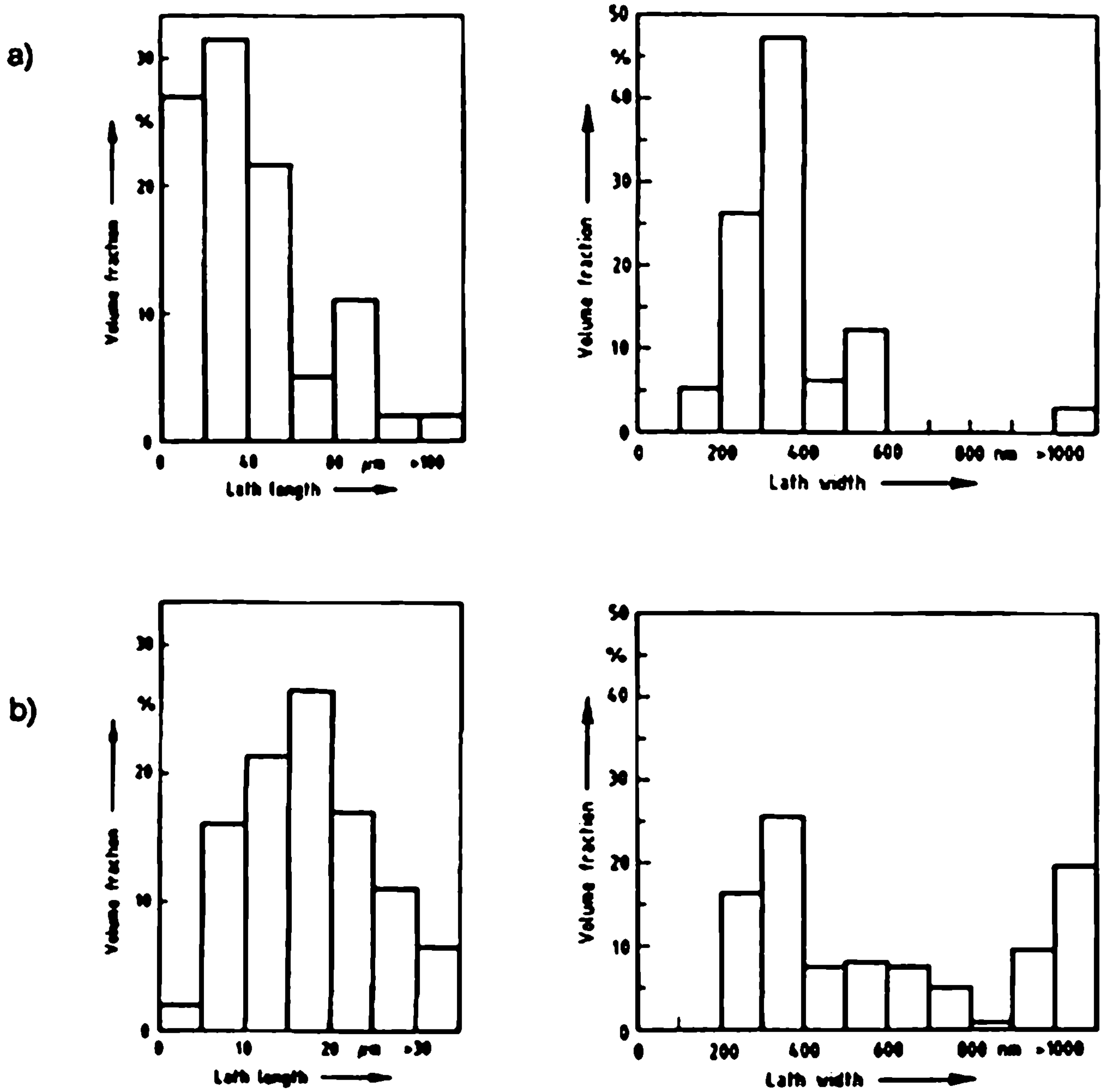


Fig. 5: Frequency distributions of lath length l and lath width w
a) treatment A, b) treatment B

Table 1: Average values of measured microstructural parameters

microstructure	w [µm]	l [µm]	M [µm]	$\rho \cdot 10^{-10}$ [cm^{-2}]
treatment A	0.37	40	1.5	5.3 ± 1
treatment B	0.53	15	1.7	3.4 ± 0.7

Discussion

The applicability of both, Equ. 1 and the Hall-Petch relationship was checked as shown in Figs. 6 and 7. Our data corroborate Kehoe's and Kelly's results giving the same slope of the straight line expected from Equ. 1 (Fig. 6). The differences of the intercept value σ_0 can be readily attributed to solid solution strengthening by Si and Mn.

On the other hand the data also fit to the Hall-Petch line observed for ferritic microstructures of the same steel (10) (Fig. 7), if only the grain size D is replaced by the average slip line length $\bar{M}$ in case of the martensite . Thus Equ. 3 holds alternatively.

$$\sigma_y = \sigma_0 + \frac{k}{\sqrt{D}} \qquad \text{Equ. 3}$$

The intercept value σ_0 is about the same as in Fig. 6 and the grain boundary strengthening factor k corresponds to the value observed for pure iron (about 20 $Nmm^{-3/2}$).

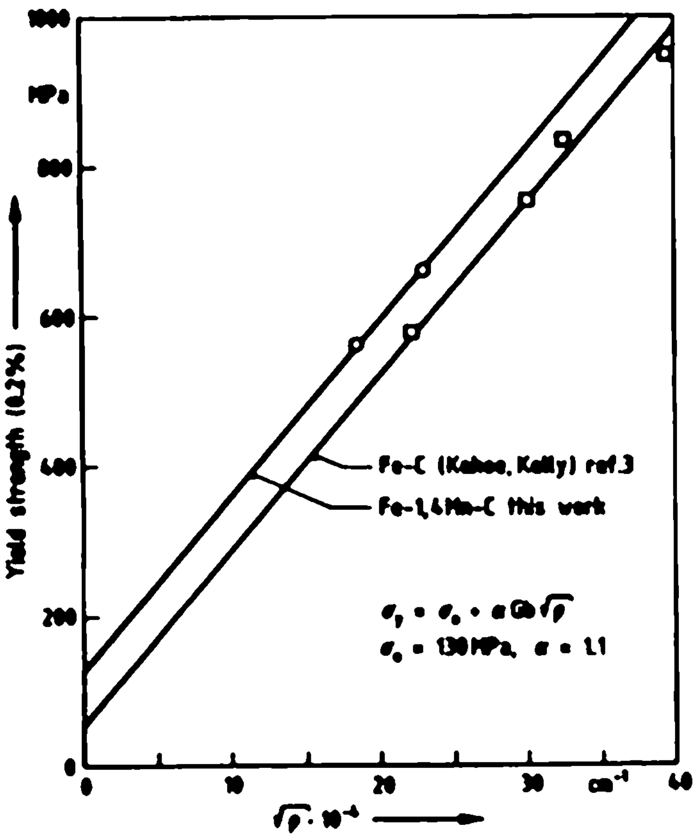


Fig. 6: Variation of yield strength with square root of dislocation density

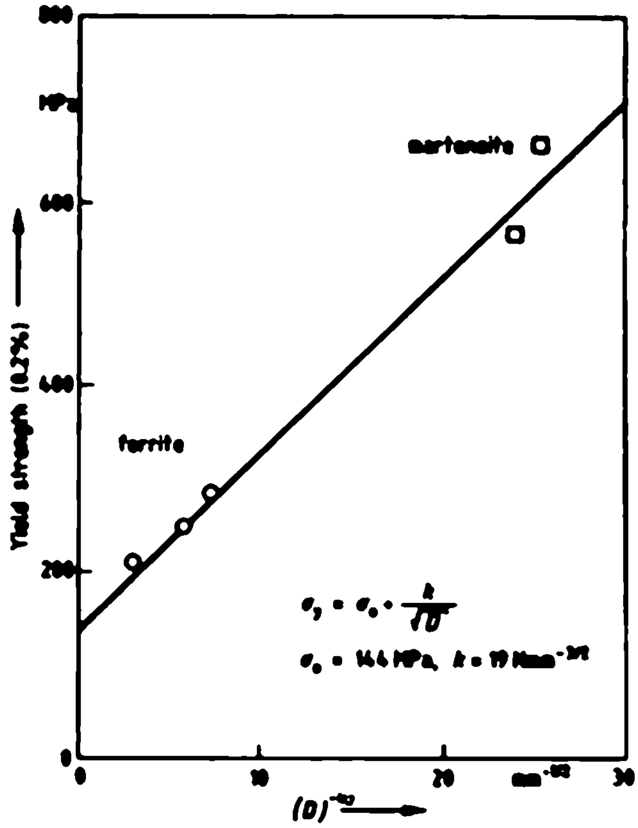


Fig. 7: Variation of yield strength with inverse square root of grain size

Summing up the results it may be said that the microstructure-strength relationship for lath martensite in our low carbon steel can be described either by Equ. 1 or by Equ. 3 but not by a linear combination of both as suggested by some other workers (4). A probable reason for these alternative descriptions is, that lowering the transformation temperature decreases the grain size and simultaneously results in an increase of the dislocation density. In other words: the dislocation density of the transformation product is a function of grain size (D or M respectively).

Since the yield strength values of the ferritic material correspond to the same Hall-Petch line (Fig. 7), it may be concluded that for them a similar relationship exists, that means that a grain size-dependent critical dislocation density has to be built up, before macroscopic yielding can commence. This idea is known as work hardening theory of the Hall-Petch relationship. There exists experimental evidence (for instance (11)) that Equ. 1 applies to cold worked iron irrespective of grain size. In fact, as already stressed by Norström (12), lath martensite resembles very much a strongly cold worked microstructure. Likewise its strength will be determined by the dislocation substructure. Other parameters such as grain size and carbon content seem to have an effect on strength through their influence on the dislocation density but not as independent strengthening mechanisms.

Acknowledgement

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