Microstructural Unit Controlling Cleavage Crack Propagation in High Strength Bainitic Steels

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Abstract. The strengthening mechanisms which are operative in bainite are very well known: small bainite packet, small width of the laths, dislocation density and size and number of carbide particles (Fe_3C), among others. Bainite packet size has been traditionally considered as the value measured by optical microscopy (OM), as electron back scattered diffraction (EBSD) technique is relatively recent. In a V-microalloyed steel with bainitic microstructure of C=0.38%, V=0.12% and N= 0.0214% the average length and width of ferrite laths and of cementite carbides were measured. On the other hand, the bainite packet size was measured by OM and EBSD with a misorientation of 15º. These values of the microstructural units have been taken in account to calculate the effective surface energy γ_p given by Griffith's model for cleavage fracture. It was concluded that bainite packet size determined by EBSD with a misorientation angle criterion of 15º was the microstructural parameter that controls cleavage crack propagation. Given the relationship between the average unit crack path (UCP) and the bainite packet size, it was concluded that the effective surface energy of cleavage fracture (γ_p) would be between 71.6 and 82.6 J m^{-2}.

INTRODUCTION

Many automotive steel parts are manufactured by forging in austenite phase and subsequently heat treated to obtain high-strength bainitic microstructure. It has long been recognised that the influence of bainite on the mechanical behaviour of a steel is difficult to understand because of the inability to attain fully bainitic microstructures at all transformation temperatures, a consequence of the incomplete reaction phenomenon [1]. In both upper and lower bainite, the boundaries between the bainitic ferrite laths within a packet are low angle boundaries, which are obstacles for dislocation movement but not for crack propagation. The strengthening mechanisms that operate in bainite are well known, and a small bainite packet size means a small lath width, low dislocation density and a low number of carbide particles (Fe_3C), among other effects [2,3]. These properties are more easily achieved for lower bainite than for upper bainite.

Several attempts have been made to quantitatively relate the microstructure of bainite to its properties [4,5]. The bainitic packet appears to be the microstructural unit controlling the cleavage resistance of low carbon bainitic steels, whose size is slightly smaller than the average unit crack path (UCP), and the critical stage in the fracture process appears to be the propagation of a Griffith crack from one packet to another [6,7]. Several packets separated by different boundaries can have a similar crystallographic orientation. This leads to the definition of two types of packets: morphological packets, defined by OM or SEM as areas enclosed by different boundaries; and crystallographic packets (grains), defined by EBSD as exhibiting crystallographic misorientation.

For other authors, it is the lath width or effective plate width that controls cleavage fracture in high carbon steels [8]. Finally, Yang et al. reported that cleavage fracture is more influenced by large carbides at the crack-tip than by any other microstructural parameter [9].

In this work the microstructural parameters (bainitic packet size, ferritic lath width and carbide width) of a high-strength bainitic steel are measured and their influence on cleavage fracture is evaluated.

EXPERIMENTAL PROCEDURE AND MATERIALS

The steel used in this work was manufactured by Electroslag Remelting (ESR) in a laboratory unit. Its chemical composition is listed in Table 1. The study of phase transformations during cooling was performed by means of dilatometric tests using a high resolution dilatometer. The specimens for dilatometry had a diameter of 2 mm and a length of 12 mm.

Table 1. Chemical composition (wt.%) of the steel manufactured by ESR.

C	Si	Mn	Al	Cr	Mo	V	N
0.38	0.28	0.90	0.022	1.01	0.20	0.12	0.0214

Tensile tests were performed according to standard EN-1002-1. The specimens for tensile tests were treated at 950°C, held for 45 min, and cooled at a rate of approximately 2 Ks^{-1}. Two specimens were tested for each austenitisation temperature.

Charpy impact testing assesses the amount of energy absorbed during the high strain rate fracture of a material and is a measure of the material's brittle fracture resistance. The Charpy test specimens were 10×10×55 mm in size with a V shaped notch 2 mm deep and a notch opening of 45°, in accordance with standard ASTM E-23. Three specimens were tested for each austenitisation temperature.

Optical microscopy (OM) and Scanning Electron Microscopy-Field Emission Gun (SEM-FEG) were used to measure the austenite grain size and bainitic packet size, respectively.

RESULTS AND DISCUSSION

Continuous Cooling Diagram and Bainitic Transformation

The continuous cooling transformation (CCT) diagram was plotted for the steel used at different cooling rates, from quenching (500 K/s) to rates as low as 0.1 K/s (Fig. 1). The heating rate to the austenitisation temperature was always the same (40K/s) and the austenitisation temperature was always 1000ºC, this being an intermediate temperature between classic heat treatment and the forging temperature of crankshafts and other automotive parts. The holding time at this temperature was 1 min. For the purposes of this research work, the most interesting transformation is the bainitic transformation during cooling, and therefore it is helpful to delimit the cooling rates that guarantee the bainitic transformation as the only or practically the only microstructure (>95%).

Fig. 1 shows the maximum and minimum cooling rates to obtain an almost completely bainitic microstructure (approximately 8 and 0.8 Ks^{-1}, respectively). Fig. 2 displays the microstructures obtained for a cooling rate of 1 Ks-1 and 5 Ks-1, respectively, showing in the first case a bainite microstructure and HV hardness of 324 and in the second case a completely martensite microstructure and hardness of 564, accordance with the CCT diagram.

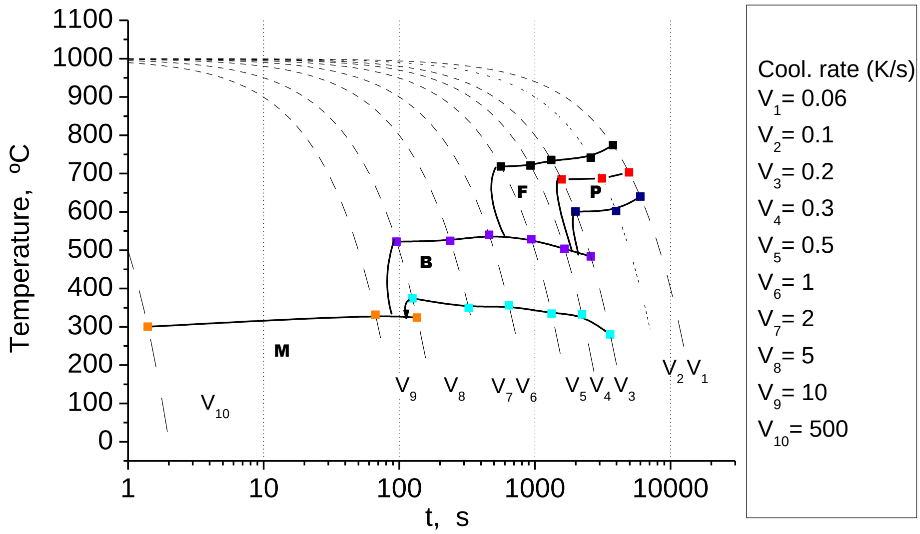


Fig. 1. CCT diagram.

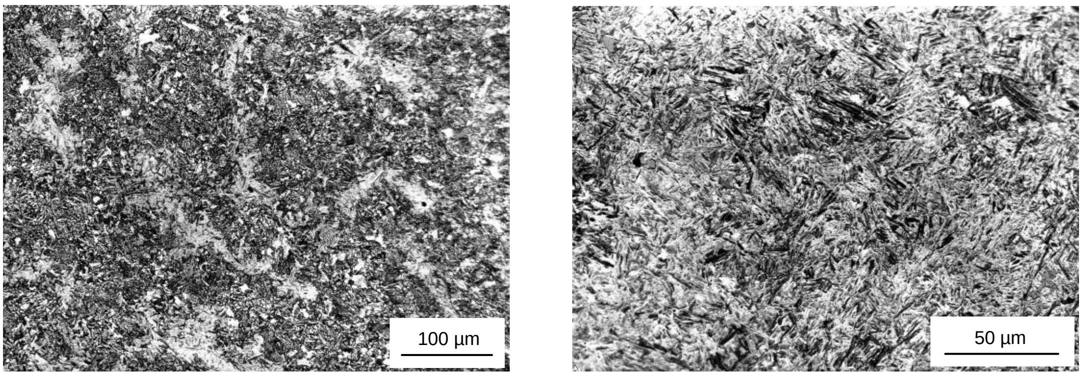


Fig. 2. Bainite microstructures. (a) 1 Ks^{-1}, HV=324; (b) 5 Ks^{-1}, HV=564.

Determination of Microstructural Parameters

The austenite grain size and the bainitic packet size were measured by optical microscopy at different austenitisation temperatures. The specimens for austenite grain size measurement were quenched in oil according to standard ASTM E-112.

On the other hand, to measure the bainitic packet the specimens were placed in a vacuum heat treatment furnace at an approximate pressure of 10^{-2} MPa and austenitised at 950°C, 1050°C and 1150°C, respectively, for 45 minutes followed by continuous cooling at the cooling rate of approximately 2 Ks^{-1} between 700°C and 400°C in an inert argon atmosphere. The packet size is given by $(l_1 l_2)^{0.5}$, where l_1 and l_2 are the average packet length and width, respectively. The average size for each treatment was taken as the mean value of more than forty measured packets. The average size varies with the austenitisation temperature, although in a different way to the austenite grain size (Table 2).

When the austenite grain size is relatively large, each grain is transformed into several bainitic packets, until finally, when the austenite grain is relatively small, each grain will be transformed into one single bainitic packet. This result is in agreement with the predictions of other authors [1], who indicate that the bainitic packet size cannot be smaller than the austenite grain size.

Table 2. Austenite grain size (D_γ) and bainitic packet (D_β) at different austenitisation temperatures.

Temperature (ºC)	950	1050	1150
D_γ (μm)	20	41	180
D_β (μm)	20	41	57

Fig. 3 displays two bainitic microstructures obtained for an austenitisation temperature of 950ºC and 1150°C, respectively, and a notable difference is seen between them, the former being much finer.

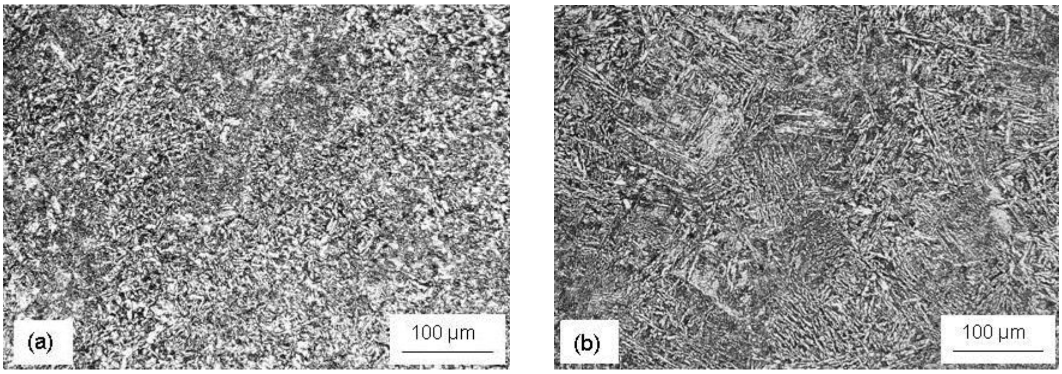


Fig.3. Bainite microstructures; (a) cooling from 950ºC; (b) cooling from 1150ºC;

The length and width of bainite (ferrite) laths in the bainitic microstructure was measured by optical microscopy following a method similar to that used to measure the bainitic packet size. The micrographs used to measure the ferrite lath length and width are the same as those used to measure the bainitic packet. The number of ferrite laths measured was more than 200 and their size distribution is shown in Fig. 4. The mean width barely varies with the austenitisation temperature, but the length is more influenced. The ferrite lath length and width in bainite are normally measured by optical microscopy, and other authors have found very similar values [12].

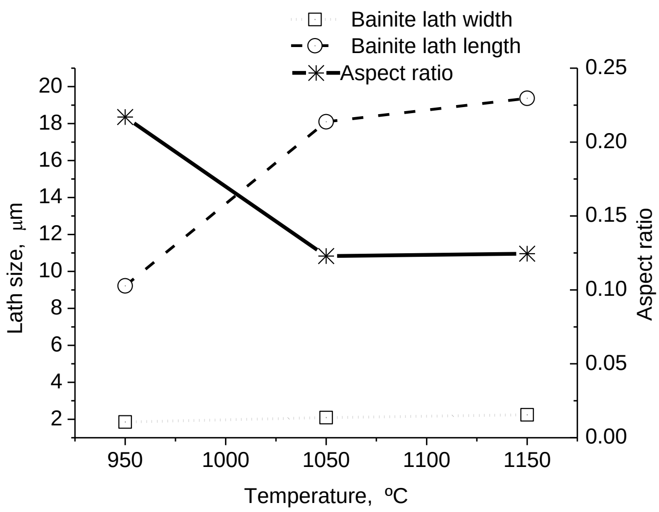


Fig. 4. Ferritic lath length and width at different austenitisation temperatures.

The length and width of cementite plates formed between the ferrite laths were measured by high resolution SEM-FEG (Fig. 5). This technique has also been used to measure the size of the nanometric VN precipitates that can be observed in the same picture, with their typical oval shape, and the results have been reported elsewhere [10]. The size distribution for carbides at a reheating temperature of 950°C is shown in Fig. 6. It can be observed that the mean width is more than one order of magnitude smaller than the width of ferrite laths.

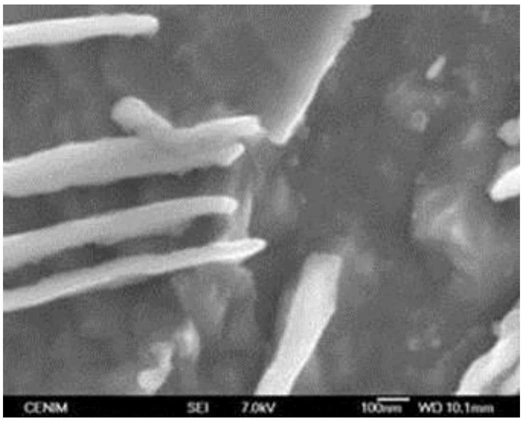


Fig. 5. SEM image showing carbides plates.

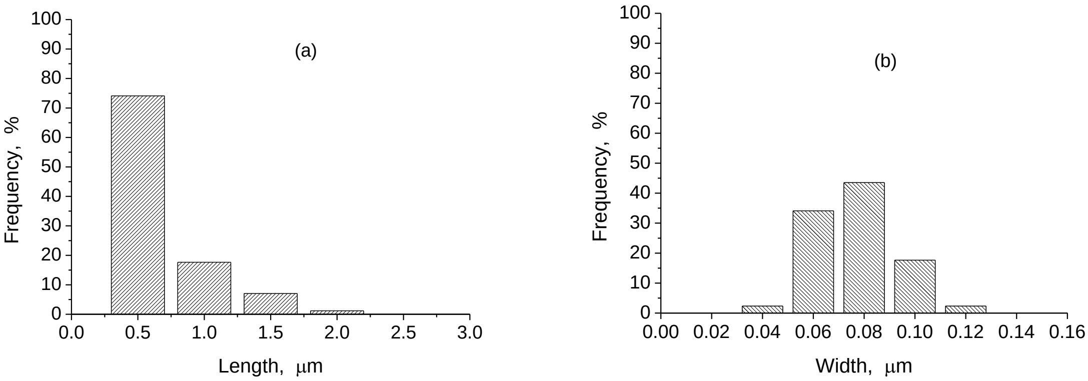


Fig. 6. Frequency of carbide (cementite) sizes. (a) length; (b) width.

EBSD analysis of the bainitic microstructure was carried out on steel specimens treated at 950°C for 45 min and cooled in the furnace. This technique offers an alternative to optical microscopy for studying the grain size (or bainitic unit) distribution of steels and has been extensively used to characterise bainite in steels. Fig. 7 (a-b) shows the Image Quality Map and the Inverse Pole Figure (Orientation Map) corresponding to the studied steel. The EBSD technique allows the units of the microstructure to be differentiated according to the misorientation across a boundary selected to consider two adjacent grains as different units. Two different grain boundary misorientation tolerance criteria were considered: a 15° misorientation between grains (Fig. 7-b) and a 5° misorientation. The bainitic unit size values determined by EBSD were of 5.9 and 4.8 mm for the two misorientation criteria mentioned above to define a grain boundary.

Microstructural parameters governing cleavage fracture

The general form of Griffith's equation is [13]:

$$\sigma_f = \left(\frac{4E\gamma_p}{\pi(1-\nu^2)d} \right)^{1/2} \tag{1}$$

where E is Young's modulus, ν the Poisson's ratio (ν =0.3), γ_p the effective surface energy of cleavage fracture, and d is a scale factor related to the microstructure of the material which is equal to the critical crack length for cleavage fracture.

The critical cleavage stress σ_f in this work has been calculated using the Von Mises criterion for a Charpy-V specimen [6], so that:

$$\sigma_f = 2.24 \cdot \sigma_y \tag{2}$$

where σ_y is the uniaxial yield stress obtained in a tensile test corresponding to 0.2% proof stress ($\sigma_{0.2}$).

The values obtained in the tensile test and Charpy impact test for an austenitisation temperature of 950°C and holding of 45 min are shown in Table 3.

Table 3. Mechanical properties for steel used. Tensile test and Charpy impact test.

$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	E (MPa)	Impact Charpy absorbed energy (J)
731	1110	205000	12

The low absorbed impact energy value (12 J) indicates a brittle fracture. The fracture with plane surfaces and a complete absence of voids clearly indicates a cleavage fracture.

According to Eq. (2), and with the value obtained for yield strength ($\sigma_y = \sigma_{0.2}$ = 731 MPa), the cleavage fracture stress σ_f would be 1637.4 MPa. In order to elucidate which microstructural units control fracture, average values of bainitic packet size, ferrite lath width and carbide plate width were calculated for treatment at 950°C. The above values are shown in Table 4 along with the γ_p calculated according to expression (1). In this expression the parameter "d" is replaced by the size of each microstructural unit.

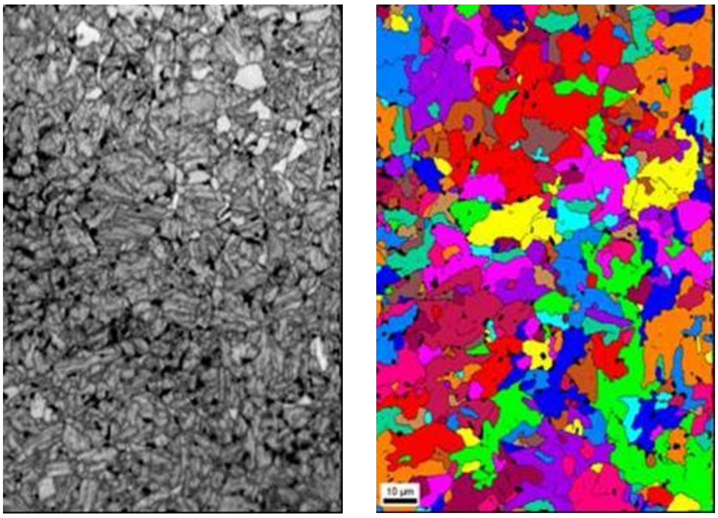
Table 4. Average sizes (d, μm) of optical microscopy bainitic packet size, EBSD (15º) bainitic packet size, ferrite lath width and carbide plate width; effective work of cleavage fracture γ_p.

Microstructural unit	Optical bainitic packet size	EBSD (15º) bainitic packet size	Ferrite lath width	Carbide plate width
Size (d, μm)	22±2	5.9±0.2	1.9	0.08
γ_p ($J \cdot m^{-2}$)	205.5	55.1	17.8	0.7

A number of researchers have successfully used equation (1) to discuss the relation between the microstructural unit and "*d*.

The value of γ_p for the microstructural unit of bainitic packet size was 55.1 J m^{-2}, and considering that the reported values for the $\langle UCP \rangle / d_{packet}$ relationship are between 1.3 and 1.5, a UCP value of between 7.7 and 8.8 μm and a γ_p value of between 71.6 and 82. 6 J m^{-2} would be obtained. These values are close to those given by Hahn et al. [25] for C-Mn steels with a polygonal ferrite microstructure. As the steel considered here presents an upper bainite microstructure with

0.38% C, low absorbed energy in the Charpy impact test and therefore a very brittle fracture, it can be expected that the γ_p values will always be lower than those corresponding to a polygonal ferrite microstructure. Consequently, it may be concluded that the bainitic packet size determined with a ≤15° misorientation angle is the microstructural unit that governs cleavage crack propagation.



(a) (b)

Fig. 6. EBSD analysis. a) Image Quality Map; b) Inverse Pole Figure (Orientation map) Misorientation = 15º.

CONCLUSIONS

The bainitic packet size measured by EBSD with a 15° misorientation criterion was equal to 5.9 μm. In contrast, the size measured by optical microscopy on a specimen thermally treated in the same conditions (950°C × 45 min), was approximately 20 μm. This parameter is the microstructural unit controlling crack propagation in a cleavage fracture. The UCP size oscillates between 7.7 μm and 8.8 μm, and γ_p varies between 71.6 and 82.6 J m^{-2}.

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