MECHANISM OF FRACTURE IN MEDIUM CARBON V-MICROALLOYED STEEL

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ABSTRACT

The relationship between microstructural parameters and fracture has been studied in air cooled vanadium microalloyed steels by means of impact testing, light microscopy and scanning electron microscopy. Large variations in impact energy are obtained as a function of test temperature and microstructure. The results show that dominantly accicular ferrite (AF) structure posess room temperature toughness superior to that of classical bainitic sheaves (BS) as revealed by impact energy level. However, AF is superior to FP-AF in term of energy transition temperature. At liquid nitrogen temperature, all steel grades show similar behavior. Transgranular cleavage is exclusive mode of fracture. Primary brittle nuclei, which control the critical tensile strength for fracture, σ_F, are found to be brittle TiN particles of diameter >2μm. Large TiN particles are friendly, because the cracks are initiated by stress much smaller than that required for crack propagation. Room temperature behavior of these steels is considerably different. The dominant fracture mechanism is still transgranular cleavage, but this is preceded by a lower (BS steels) or higher (AF steels) degree of ductile fracture.

1. Introduction

Production of different variants of medium carbon continuously cooled bainites have received attention due to bainitic or predominantly bainitic microalloyed forging steels have been shown to exhibit an improved toughness. In most studies devoted to bainitic steels, the microstructure is described either as bainitic or acicular [1-10], without more detailed specification of neither the ferrite morphology nor the residual phases. On the other hand, there is no full agreement upon influence of bainite on toughness, i.e. bainite is either beneficial [1-10] or detrimental to toughness [11-13].

The aim of this paper is to illustrate the influence of different variants of bainitic microstructure on mechanisms of fracture in medium carbon V-microalloyed steel developped for oil sucker rod.

2. Experimental

Chemical composition of steels tested in this work is given in table 1.

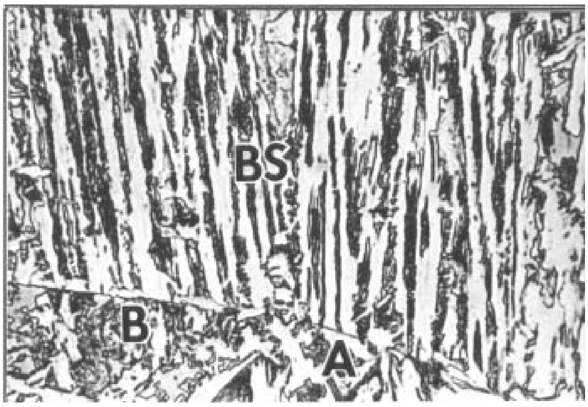
Table 1. Chemical composition of tested steels

Steel	C	Mn	Si	P	S	Cr	Ni	Mo	V	Ti	Al	O	N
L-22	0.26	1.75	0.31	0.010	0.010	0.37	0.18	0.04	0.17	0.01	0.03	61	21
L-3	0.30	1.51	0.32	0.006	0.007	0.28	0.18	0.04	0.10	0.01	0.02	36	121

Steels were produced as laboratory ingots, melted and casted in vacuum. Ingots were removed from moulds immidiateley after the formation of solid core, which gave rise to cooling rate between 39 and 44°C/min, in the center and on the surface, respectively. These cooling rates are known to be effective in producing the fine TiN particles during solidification, capable of imposing a pinning effect on austenite grain boundaries during subsequent heating [14]. After solidification, ingots were fabricated by full hot rolling into 22mm bars. Micromechanism of fracture in medium carbon V-microalloyed steel was evaluated by means if impact testing (standard Charpy V-notch longitudinal specimens were machined from the center of the bar and tested at +20 and -196°C), light microscopy (Conventional metallographic techniques were used for revealing the microstructure. The transverse specimens were etched in a 2% nital solution, or in a saturated aqueous solution of picric acid alternatively with polishing, in order to reveal the ferrite and the prior austenite grain boundaries, respectively. Before etching in picric solution, the specimens were heated at 450°C for 24hrs) and SEM microscopy. To reveal the nature of second phase particles and impurities, EDAX analysis was also performed.

3. Results

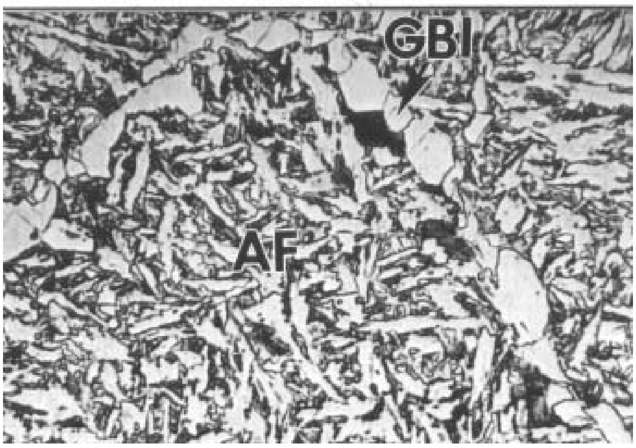
3.1 Light Metallography
Typical microstructure of steel L-22 is shown on figure 1.



30μm

Figure 1. Steel L-22; grain boundary nucleated bainite sheaves (BS).

Grain boundary nucleated sheaves of parallel ferrite plates or individual ferrite plates which, according to microstructural definition of bainite proposed by Aaronson [15], contain non-lamellar dispersion of carbides, or alternatively, coexist with aligned, elongated, parallel islands of retained austenite and/or M/A constituent [16], are referred to as bainitic sheaves (BS). The grain boundary nucleated sheaves have been recognized [17] to be quite similar in morphology to Widmanstatten sideplates. According to some authors [18] the only distinct morphological difference, at the light microscope level, is that bainitic ferrite is nucleated directly at an austenite grain boundary, while Widmanstatten sideplates grow from the grain boundary allotriomorphs, and the coalescence of them leads to the formation of thicker plates. However, nucleation of Widmanstatten ferrite at austenite grain boundary as well as its growth from allotriomorphs are considered equally feasible by the other authors [16], and a distinction, on the light microscope level, is assumed to be that the Widmanstatten ferrite crystals are on the average considerably larger [18]. Distinction is even more complicated if within a given colony of parallel sideplates, some are still Widmanstatten, while the others are bainitic, as pointed out by Aaronson [15]. The present results are inconclusive in this regard, but an important feature of the ferrite plates, assumed to be upper bainite in this work, is that even the adjacent plates constituting a sheaf can nucleate one directly at an austenite grain boundary, while the other can grow as secondary sideplate from a grain boundary allotriomorph (labelled A and B, respectively in Fig.1).



30μm

Figure 2. Intragranularly nucleated acicular ferrite (AF). Grain boundary ferrite (GBI) decorates the former austenite grain boundaries.

Microstructure of steel L-3 consists dominantly of intragranularly nucleated mostly needlelike plates, which radiate in many directions. They are referred as acicular ferrite (AF). Acicular ferrite is observed to be a predominant morphology in Ti-bearing steel. A similar microstructure has been observed in low-carbon weld deposits [19], low-carbon wrought microalloyed steel [20,21], and most recently in a medium carbon V-microalloyed steel [22]. The acicular ferrite is assumed to be either intragranularly-nucleated bainite [23], or Widmanstatten ferrite [24]. More details are discussed elsewhere [25,26].

3.2 Mechanical properties

Table 2. Tensile properties and CVN Impact energy of tested steels

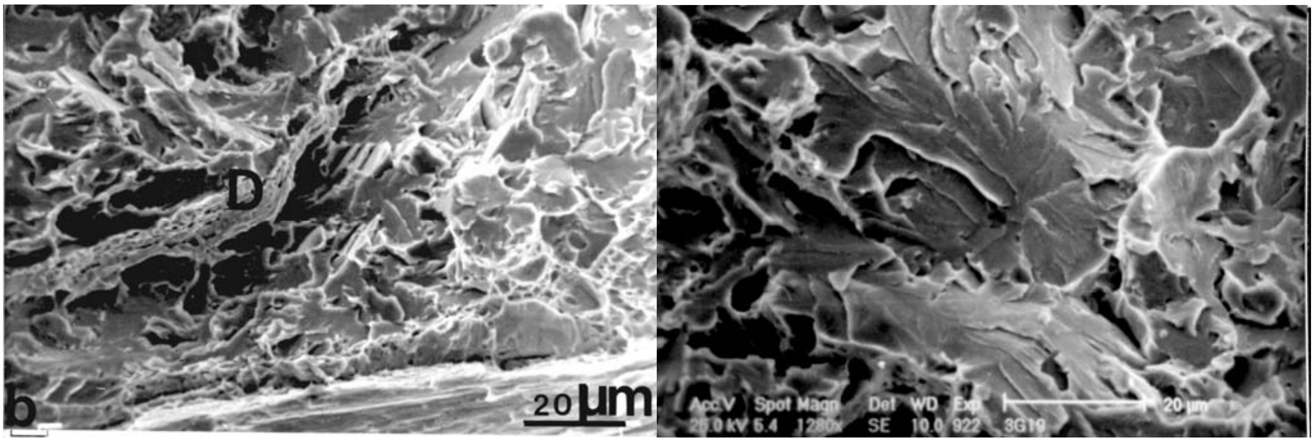
Steel	Tensile properties			CVN Impact energy, J							Transit. temp. 27J, °C
	YS, MPa	TS, MPa	EL, %	+20°C	0°C	-20°C	-40°C	-60°C	-80°C	-196°C	
L-3	587	850	17	58	46	30	32	22	15	7	-42
L-22	529	904	14	26	-	-	-			2	NA

NA – Not Applicable

Data from table 2 show that steel L-3 has higher yield strength, elongation and CVN impact energy and lower tensile strength in comparison to L22 steel. Also, transition temperature evaluated using 27J criterion is -42°C for L-3 steel, while it was not possible to estimate transition temperature of L22 steel using the same criterion due to very low toughness, even on room temperature.

3.3 SEM obeservations

a) -196°C Temperature



(a) (b)

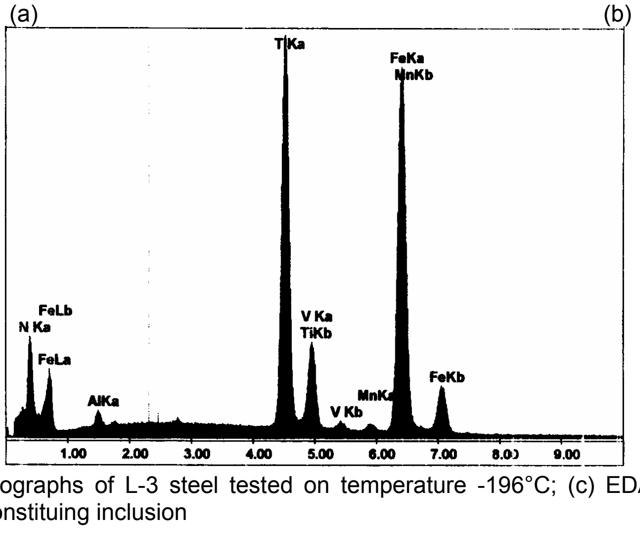
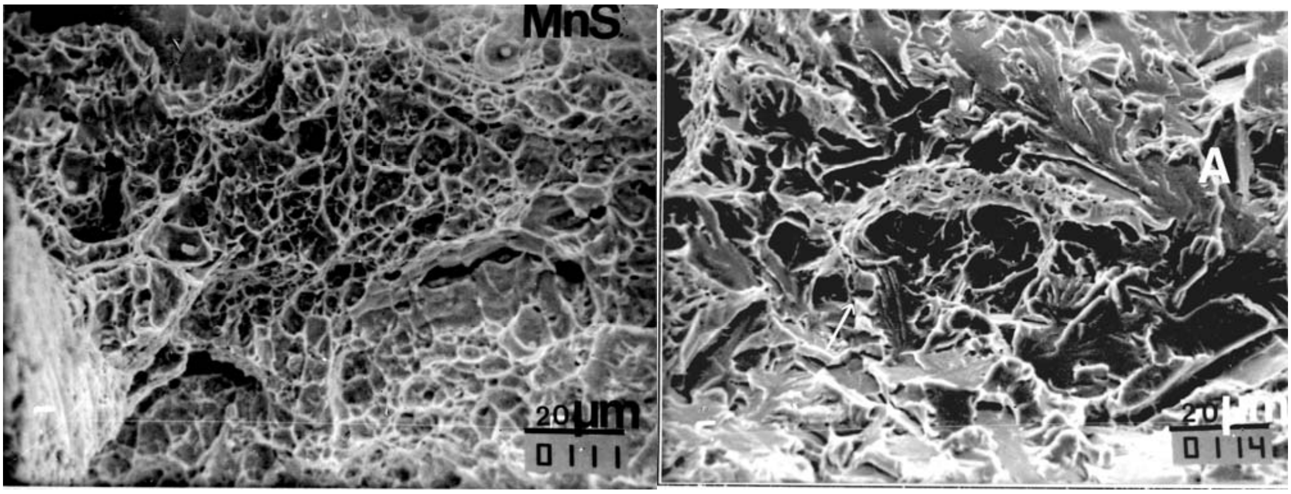


Figure 3. (a) and (b) SEM micrographs of L-3 steel tested on temperature -196°C; (c) EDAX spectra from inclusion with accompanying list of elements constituing inclusion

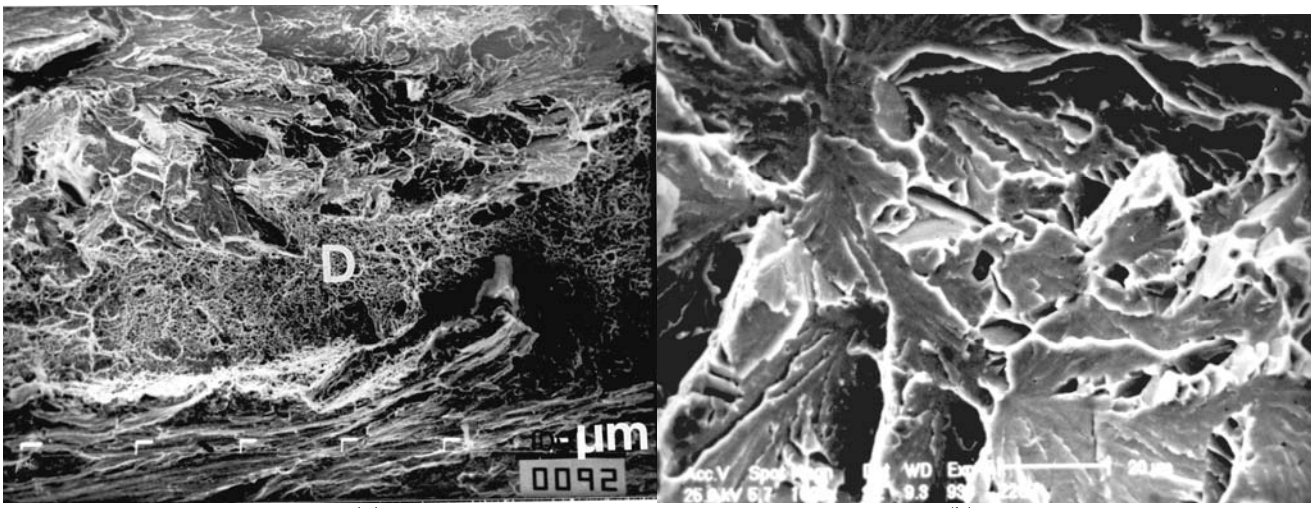
In both specimens, independent of microstructure, the brittle fracture is present, as shown on Figures 3a and 3b. One single clear origin for cleavage fracture was never observed, indicating multiple initiation sites. Various microstructural features were found to be associated with cleavage origins, such as: (i) TiN based inclusions located dominantly in the middle of large facets (fig 3a); (ii) formation of complex or agllomerated inclusions (depending on content of Ti, N, V, N, Mn, S, O etc), figs 3b and 3c; grain boundary particles (usually carbides).

b) room temperature



(a) (b)

Figure 4. SEM micrographs of L-3 steel tested on room temperature (a) ductile fracture features (b) Cleavage fracture features



(a) (b)

Figure 5. SEM micrographs of L-22 steel tested on room temperature (a) ductile fracture features (b) Cleavage fracture features

Fractured surface is, in both specimens, characterized by both ductile and brittle fracture features, indicating that room temperaure is within the ductile-brittle transition region. In L-3 steel, large ductile zone of dimples is observed along the notch root (fig 4a), where the size is even greater than 1000μm. Inside small dimples inclusions are not visible, probably suggesting very small size of second phase particles. Presence of facets starts from the point below ductile zone, together with other microstructural features associated with cleavage origins on -196°C. On the other hand, it seems to be that grain boundary carbides are the most important microstructural features associated with cleavage origin on room temperature. In L-22 steel, features are simillar to those for L-3 steel, while the size of ductile zone (D on Fig 5a) is considerabely smaller, and the origins of cleavage initiation are much closer to notch root. These differences result in lower toughness.

4. Discussion

At liquid nitrogen temperature, all steel grades show similar behavior. Transgranular cleavage is exclusive mode of fracture. Primary brittle nuclei, which control the critical tensile strength for fracture, σ_F, are found to be brittle TiN particles of diameter >2μm. Large TiN particles are friendly, because the cracks are initiated by stress much smaller than that required for crack propagation. This means that cracks ill become blunted out, what will make them inactive before the stress for crack propagation is achieved. Carbides and martensite/austenite/carbide (MAC) constituent are tentatively identified as secondary brittle fracture nuclei, but they are of less significance. As the critical stage of brittle fracture is crack propagation through particle/matrix interface, the morphology and ferrite grain size play little role. Calculation of maximum tensile stress below the notch, σ_{max}, and critical tensile strength for fracture, σ_F, under the assumption that diameter of TiN particle, which are the primary nuclei, are equal to penny shaped crack size [27], have shown that the requirements for crack propagation through particle/matrix interface, $\sigma_{max} > \sigma_F$, is satisfied from the beginning of fracture process at liquid nitrogen temperature in all steels studied in this work.

Room temperature behavior of these steels is considerably different. The dominant fracture mechanism is still transgranular cleavage, but this is preceded by a lower (BS steel-L22) or higher (AF steel – L-3) degree of ductile fracture. Calculation have shown that at the beginning of fracture , $\sigma_{max} < \sigma_F$. This means that the brittle crack initiated on brittle particles can not propagate; instead, the ductile crack will be initiated and propagated. During propagation, ductile crack is assumed to accelerate, what, in turn, increases the strain rate, and consequently, σ_Y and σ_{max}. At a critical ductile crack length, critical condition, $\sigma_{max} > \sigma_F$, is achieved, and brittle cracks, initiated in brittle particles ahead of the ductile crack tip are activated. These propagate across particle/matrix interface and cause fracture [28]. Higher toughness of steels with AF structure requires a longer ductility crack to be formed, than in steels with BS structure, before requirement for brittle fracture, $\sigma_{max} = \sigma_Y \cdot n > \sigma_F$, is attained, because the strain hardening exponent (n) of the former steel is much lower and product $\sigma_Y \cdot n$ is smaller in spite of σ_Y is higher. The overall contribution of ductile fracture to the toughness is relatively small, because the shear decohesion mechanism, which dominates ductile fracture in both steels, is characterized by a low expenditure of energy. In spite of TiN inclusions are present, the primary nuclei are assumed to be carbides, smaller than 1μm. The TiN-cracks are blunted out before the conditions for cleavage are attained. This can be ascribed to influence of a large plastic zone which is produced ahead of the ductile crack. In addition to being more resistant to brittle crack propagation across particle/matrix interface, the steels with AF structure show the susceptibility to cracks being arrested at the grain boundaries, presumably AF plate boundaries. This feature is observed only in steels with AF and not with BS structure, providing thus additional barriers to crack propagation in former.

5. Summary

The relationship between microstructural parameters and fracture has been studied in air cooled vanadium microalloyed steels by means of impact testing, light microscopy and scanning electron microscopy. Large variations in impact energy are obtained as a function of test temperature and microstructure. The results show that accicular ferrite (AF) and a multiphase structure consisting of ferrite-perlite (FP) and 30-70% AF posess room temperature toughness superior to that of classical bainitic sheaves (BS) as revealed by impact energy level. At liquid nitrogen temperature, transgranular cleavage is exclusive mode of fracture. Primary brittle nuclei, which control the critical tensile strength for fracture, σ_F, are found to be brittle TiN particles of diameter >2μm. Large TiN particles are friendly, because the cracks are initiated by stress much smaller than that required for crack propagation. Room temperature behavior of these steels is considerably different. The dominant fracture mechanism is still transgranular cleavage, but this is preceded by a lower (BS steels) or higher (AF steels) degree of ductile fracture.

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