Fatigue behavior of homogeneous-microstructure and mixed-microstructure steels

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RIASSUNTO. Gli stampi per componenti in materia plastica utilizzati nell'industria automobilistica, come per esempio paraurti e cruscotti, sono solitamente lavorati per asportazione di truciolo da grandi blocchi di acciaio prebonificato, generalmente in acciaio ISO 1.2738 (40CrMnNiMo8-6-4).

L'asportazione di materiale nel corso della lavorazione espone, in parte della superficie dello stampo, l'acciaio che era a cuore durante i processi di colata e di trattamento termico.

Da studi precedenti condotti sull'acciaio ISO 1.2738 è stato riscontrato che a causa delle elevate dimensioni dei blumi, il trattamento termico produce microstrutture miste, variabili con continuità in funzione della distanza dalla superficie temprata. In prossimità della superficie si osserva prevalentemente martensite rinvenuta, la cui frazione, tuttavia, decresce rapidamente con la profondità; le bainiti, superiore ed inferiore (modificate dal rinvenimento), sono i costituenti prevalenti nell'insieme. Infine, la perlite appare gradualmente a profondità più elevate e diventa il principale costituente a cuore.

Tale variabilità di microstrutture si riflette direttamente sulle proprietà meccaniche dello stampo, con una riduzione continua della durezza e delle proprietà tensili passando da superficie a cuore, e valori di resilienza e di tenacità a frattura insoddisfacenti (dell'ordine di 10 J e di 40 MPa√m rispettivamente) e molto inferiori a quelli conseguiti dal medesimo acciaio in una condizione di trattamento di bonifica ottimale.

Poiché gli acciai per stampi per materie plastiche sono generalmente utilizzati nella fabbricazione di milioni di pezzi (ad esempio per la produzione di un modello di autovettura), essi sono soggetti anche a sollecitazioni di fatica di natura meccanica e termica (derivante dalla pressione di iniezione del polimero e dalla sua temperatura di processo, rispettivamente).

A tale proposito, benché questi acciai vengano utilizzati da diversi anni, il loro comportamento a fatica, in particolare in relazione alle microstrutture miste, non è stato molto studiato. Pertanto è stata svolta un'indagine accurata sul comportamento a fatica di due acciai commerciali, effettivamente utilizzati per la produzione di stampi per paraurti: il tradizionale acciaio ISO 1.2738 (0.42 %C, 1.5 %Mn, 2.0 %Cr, 0.21 %Mo, 1.1 %Ni, 0.08 %V) e un acciaio microlegato (0.28 %C, 1.6 %Mn, 1.4 %Cr, 0.6 %Mo, 1.1 %Ni, 0.12 %V, 0.02 %Nb, 0.0013 %B) recentemente proposto per tali scopi.

A differenza del blumo di acciaio ISO 1.2738 (la cui microstruttura è stata precedentemente descritta), quello dell'acciaio microlegato presenta in superficie una microstruttura mista di bainite e martensite rinvenuta, con un contenuto di bainite crescente verso il cuore del blumo (completamente bainitico).

Per chiarire l'influenza della microstruttura sul comportamento a fatica di questi acciai, sono state condotte delle prove di fatica anche su campioni di acciaio ISO 1.2738 ritrattati termicamente in laboratorio e che presentano, al termine di tale trattamento, delle microstrutture omogenee (perlite e martensite rinvenuta) o mista (bainite e martensite non rinvenuta).

Dalle prove di fatica è stato riscontrato che i campioni ricavati a diversa profondità dal blumo di acciaio ISO 1.2738 e da quello microlegato, presentano un comportamento a fatica non molto dissimile. In particolare l'acciaio ISO 1.2738 presenta un esponente di Paris in un range che va da 2.4 a 3.2, con una velocità di crescita di cricca che diminuisce dalla superficie a cuore, mentre l'acciaio microlegato presenta un andamento generale e una velocità di crescita di cricca paragonabili all'acciaio ISO 1.2738, ma una

pendenza lievemente maggiore nel tratto lineare.

Confrontando tali risultati con quelli ottenuti dai campioni ritrattati di acciaio ISO 1.2738, appare evidente che, per ΔK maggiori di 20 MPa√m, le microstrutture omogenee di martensite rinvenuta e di perlite presentano una velocità di crescita della cricca di fatica rispettivamente maggiore e minore dei campioni non ritrattati, con una pendenza simile nel tratto lineare. In tale contesto, la ripida curva di Paris (coefficiente ~ 9.7) associata al campione ritrattato con microstruttura mista è attribuibile alla presenza di martensite non rinvenuta. In particolare, questo tipo di microstruttura, e quindi di comportamento a fatica, può essere riconducibile a quello delle zone termicamente alterate presenti in uno stampo reale che abbia subito delle modifiche e/o riparazioni locali per weld bed deposition.

Le superfici di frattura dei campioni di fatica, esaminate al SEM, presentano morfologie simili, spesso riconducibili alla microstruttura bainitica prevalente nei due acciai, con la presenza di qualche area isolata di frattura intergranulare. La rottura finale dei campioni avviene sempre in modo fragile, mediante un meccanismo misto di frattura intergranulare e per clivaggio.

In conclusione, questi risultati dimostrano che il comportamento a fatica di questi acciai è influenzato dalle microstrutture miste, soprattutto nell'acciaio ISO 1.2738 dov'è presente una variazione microstrutturale maggiore nell'intera sezione del blumo. Inoltre, dai ritrattamenti eseguiti su alcuni campioni di questo acciaio, è evidente come una struttura perlitica presenti una velocità di crescita della cricca di fatica inferiore del 30% (nel range che va dai 20 ai 50 MPa√m) rispetto a quella di una martensite rinvenuta, benché quest'ultima possieda una tenacità a frattura superiore.

ABSTRACT. In last years, the growing production and consumption of large plastic components, usually employed in the automotive industry, has notably influenced the plastic mold market. Medium carbon low alloyed steels, such as ISO 1.2738, have long been applied for these purposes. The ISO 1.2738 mold steel is usually machined from large pre-hardened blooms. Due to the dimensions, their heat treatment yields mechanical properties and mixed microstructures continuously varying from surface to core. Although these steels have been used for several years, their fatigue behavior, as well as the behavior of similar mixed microstructures steels, is not well known.

The effect of these mixed microstructures on the fatigue crack growth (FCG) behavior, in the threshold and Paris regime, has been reported. FCG tests were carried out on the traditional ISO 1.2738 steel and on a quenched and hardened microalloyed steel recently proposed for plastic molds.

Moreover, in order to clarify the interplay between the microstructural features and the fatigue behavior, fatigue crack growth tests were performed on ISO 1.2738 steel re-heat-treated samples with homogenous microstructures (pearlite or tempered martensite) and results were compared with those obtained from mixed microstructure samples cut from original blooms.

After the tests, scanning electron microscopy (SEM) observations of fatigue fracture surfaces were carried out to understand the influence of microstructure morphologies on the FCG resistance.

PAROLE CHIAVE: plastic mold steels, mixed microstructures, fatigue.

1 INTRODUCTION

Plastic mold steels require several properties such as wear resistance, high hardenability, good polishability, and dimensional stability during heat treatment. Therefore, quenched and tempered steels have long been used for the purpose. Automotive industries apply these steels very intensely, with the ISO 1.2738 steel (40CrMnNiMo8-6-4) being traditionally employed in the injection molding of large plastic components such as bumpers and dashboards.

Previous studies performed on samples cut from an actual pre-hardened large ISO 1.2738 steel mold [1,2] have shown the occurrence of continuously varying mixed microstructures ranging from the surface to the core of the block, being tempered martensite/bainite and bainite/pearlite, respectively. These mixed microstructure exhibit very low toughnesses and impact absorbed energies (40 MPa√m and 10 J on the average), remarkably smaller than those achieved in samples with similar tensile strength but individually re-heat-treated to yield a fully tempered martensite structure after quenching and tempering [1].

Since the plastic mold steels are usually used for the production of millions of pieces (e.g. production of one car model), they are subjected to a severe mechanical and thermal fatigue (due to the injection pressure and to the temperature of the polymer), so that the fatigue behavior of these steels is critical. Therefore, the improvement of fatigue strength and fatigue crack growth resistance of mold materials is strongly required for fracture risk control.

In an ongoing experimental effort [3], FCG data of mixed microstructures, arising from the whole section of an actual ISO 1.2738 steel pre-hardened bloom, are compared with similar data obtained from tests performed on specimens cut from the same bloom and re-heat-treated to yield various homogeneous or mixed microstructures.

Moreover, since ordinary mold stress histories can be considered as a sequence of quasi-constant amplitude cycles, fatigue crack growth and/or residual fatigue life can be straightforward calculated, if appropriate data are available.

In the last decade, steelworks have been also proposing quenched and tempered microalloyed steels for plastic molds. Previous studies [2,4] have shown that these steels have more uniform mechanical properties throughout the bloom section and a better fracture toughness than the ISO 1.2738 steel (even if not definitely superior). Thus fatigue tests on samples cut from a commercial microalloyed steel bloom have also been obtained to get the overall behavior scenario.

2 MATERIALS, SAMPLING AND TESTING

The chemical composition of the examined steels is reported in Tab. 1. Both the ISO 1.2738 steel and the microalloyed steel are designed for quenching and tempering heat treatments. In respect to the ISO 1.2738, the microalloyed steel is characterized by lower C and higher Mo contents and by the presence of microalloyed elements, such as B, Nb and V (the last is also present in the ISO 1.2738 in order to limit grain coarsening during the long steelwork heat treatments). Zr is an impurity arising from the ingot casting process. In particular, the lower C and Cr contents in the microalloyed steel improve the weldability, while keeping a similar strength and hardenability (due to the higher Mo and microalloying elements) [2].

Both the steels were obtained from commercial pre-hardened steel blooms subjected to previously similar steelwork treatments, namely: ingot casting, hot forging (in order to reduce the chemical and microstructural inhomogeneity), dehydrogenizing, austenitizing, quenching, double tempering [1,2]. At the end of the steelwork operations, the ISO 1.2738 bloom measured 2970 (L) x 1285 (T) x 1190 (S) mm, whereas the microalloyed bloom steel was 2900 (L) x 1260 (T) x 1020 (S) mm long (L, T and S letters are forging reference directions and identify the direction of the principal deformation, the direction of the least deformation and the third orthogonal direction, respectively).

The microstructures and the mechanical properties of these blooms were previously reported [1,2]. The regions of the 1.2738 steel bloom examined consisted of: i) mixed upper bainite and fine pearlite in the core region (yield strength σ_y ~ 650 MPa); ii) tempered bainite in the mid-depth region (σ_y ~ 800 MPa); iii) tempered martensite (with some temper modified retained austenite) in the two opposite surface regions (σ_y ~ 900 MPa), considered equivalent due to the symmetry of the production process [1]. The surface region of the microalloyed steel bloom consisted of mixed tempered martensite and bainite (fracture toughness, K_{Ic}, ~ 55 MPa√m and σy ~ 950 MPa); the bainite contents increased in the core region (K_{Ic} ~ 45 MPa√m and σ_y ~ 1000 MPa) [2].

Further 1.2738 test samples were cut from the as-received bloom and subjected to three different re-heat-treatments. All of them were austenitized at 850 °C for 1 h and then cooled in different modes: i) the first sample (P) was held at 600 °C for 7 h and air cooled (yielding a 345 HB final hardness); ii) the second sample (TM) was quenched in air from 850°C and tempered at 590 °C for 3 h (447 HB); iii) the third one (BBM) was held at 340 °C for 7 h and air cooled (452 HB).

Metallographic observations showed that the P sample showed a pearlite microstructure (possibly with a small martensite fraction) [5], the TM sample consisted of tempered martensite [1], whereas the BBM sample consisted of upper and lower bainite, with some fractions of martensite [1].

Fatigue crack growth tests were carried out according to the ASTM E647 standard, at room temperature. Tests were performed using a constant amplitude sinusoidal loading with a load ratio of R = 0.1. CT (Compact Tension) and SENB3 (Single Edge Notched Bend 3-point bend) specimens were tested, all machined from

	C	Mn	Cr	Ni	Mo	Si	V	Nb	Zr	B	S	P
ISO 1.2738	0.42	1.5	2.0	1.1	0.21	0.37	0.08	-	-	-	0.002	0.006
Microalloyed	0.28	1.6	1.4	1.1	0.60	0.28	0.12	0.02	0.03*	0.0013	-	0.007

Table 1: Chemical analysis of the examined steels (wt. %).

**Estimated from microprobe results.*

the surface to core of the ISO 1.2738 and microalloyed blooms and fabricated in LT orientation (in respect to the original blooms). The CT samples had a nominal thickness B = 6 mm and width W = 50 mm [6], whereas the SENB3 specimens had a nominal thickness B = 12.5 mm and width W = 25 mm [7]. The crack length of the CT samples was measured by optical microscopy on both polished surfaces samples (the fatigue test was interrupted to perform each measurement). The fatigue crack length of the SENB3 samples was monitored continuously by using a compliance method, using a crack opening displacement (COD) gauge, and was recorded at fixed crack length intervals. The crack growth test results were summarized in terms of FCG rate (da/dN) versus stress intensity factor range (ΔK) curves using the secant method for the K-decreasing cases (points with FCG rates lower than 10^{-11} m were discarded), and the incremental polynomial method (of order 2) for the K-increasing cases [6].

Series of rotating bending fatigue S-N tests were performed according to the staircase method, upon smooth cylindrical samples, in order to determine the fatigue stress corresponding to a 50% survival probability after $4.2\text{x}10^6$ cycles.

3 RESULTS

The fatigue crack growth rates of the homogeneous and mixed microstructures, from threshold to Kmax controlled instability, are herein stated. Results are expressed in terms of the crack tip stress-intensity factor range (ΔK), defined by the theory of linear elasticity.

1.2738 Steel FCG Behavior

The FCG behavior of the 1.2738 steel samples pertaining to different positions inside the bloom (regardless of the sample type and measurement techniques) is showed in Fig. 1. There are no evident differences among the FCG behavior of the mixed microstructures arising from the as-received bloom. The Paris slope is similar (in the 2.4 to 3.2 range) with decreasing overall FCG rates from surface to core.

The FCG curves of the re-heat-treated samples, in the Paris region, are plotted in Fig. 2. Fully tempered martensite or perlitic samples represent the possible microstructures at the surface and at the core of the original 1.2738 steel bloom, whereas mixed bainite and (untempered) martensite specimens should depict the worst ever scenario encountered in molds modified or repaired by weld bed depositions.

The re-heat-treatments modify the FCG behavior of the ISO 1.2738, with the exception of the TM samples having a similar trend to that of the mixed microstructures (although the former broke at a higher ΔK, certainly due to its higher fracture toughness [1]). The pearlite (P) sample shows a similar slope in the linear range, but lower FCG rates than the core bloom sample, where some bainite was also present. Finally, the BBM sample present the worst fatigue behavior in the overall scenario, not comparable with the others results,

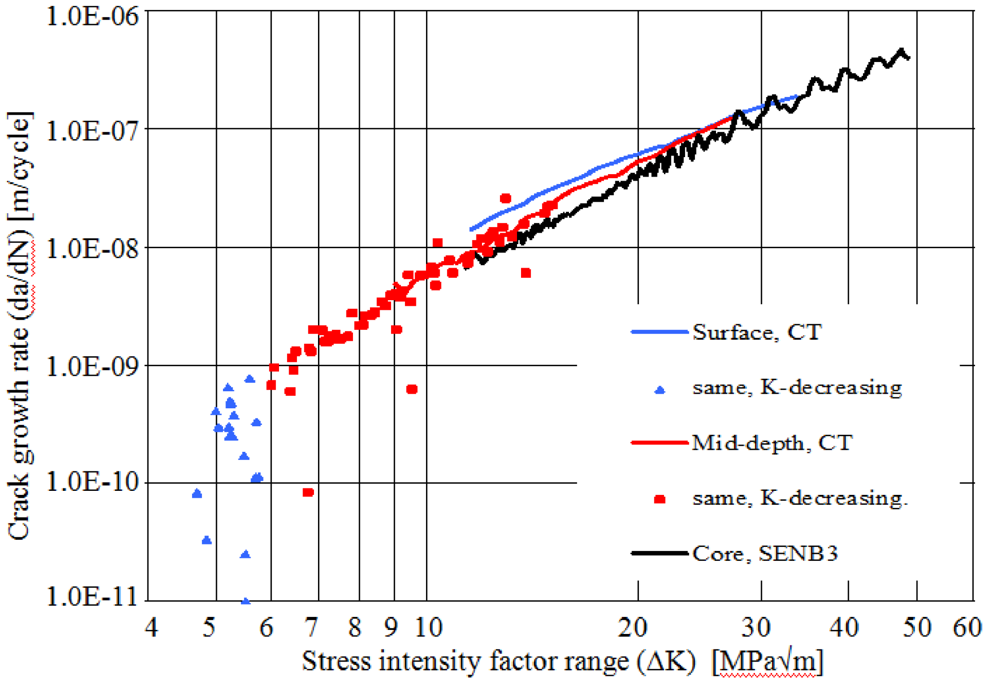


Figure 1: Steel 1.2738: SENB3 or CT samples, representative of bloom positions. Paris plot of K-increasing (lines) or K-decreasing (isolated points) tests.

yielding a Paris slope of 9.7, about 3 times larger than all other samples, thus resulting in much larger FCG rates at high ΔKs.

Microalloyed Steel FCG Behavior

In Fig. 3, results obtained from the surface sample of the microalloyed steel bloom are compared with those of the ISO 1.2738 bloom ones. The microalloyed steel exhibits a lower FCG rate at stress intensity factor ranges (ΔK) up to about 15 MPa√m. Nevertheless, the overall Paris slopes of the microalloyed steel specimens are higher, particularly that of the core specimen, and their FCG rates eventually exceed those of the 1.2738 bloom samples at ΔK values higher than 20 MPa√m.

In the FCG threshold region, the possible diffe-

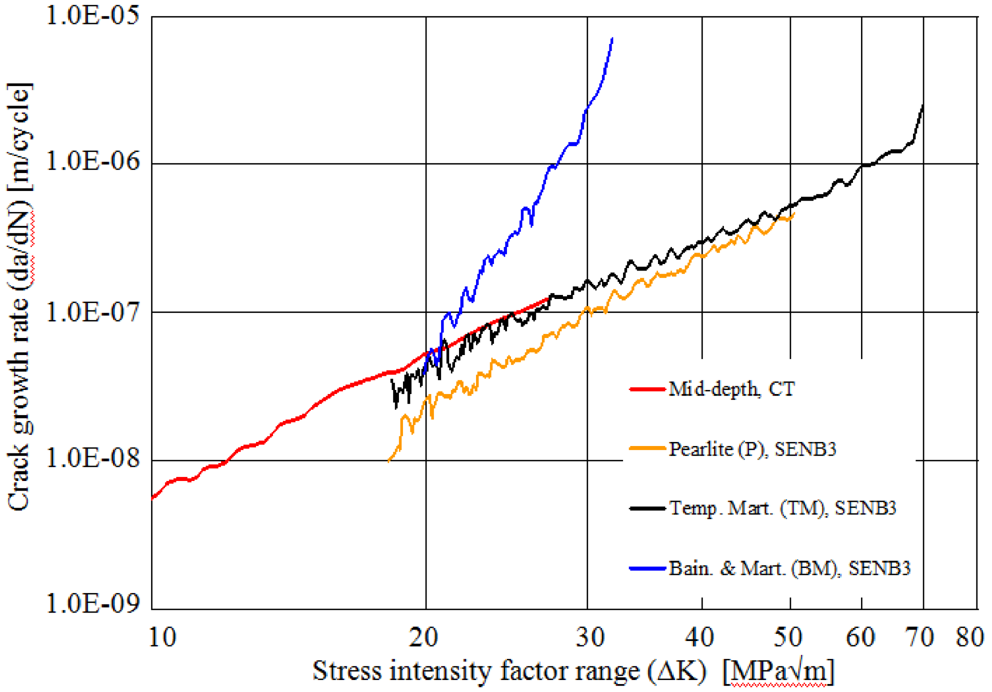


Figure 2: 1.2738 Steel: re-heat treated SENB3 samples, Paris plot of K-increasing test results and comparison with the bloom mid-depth material.

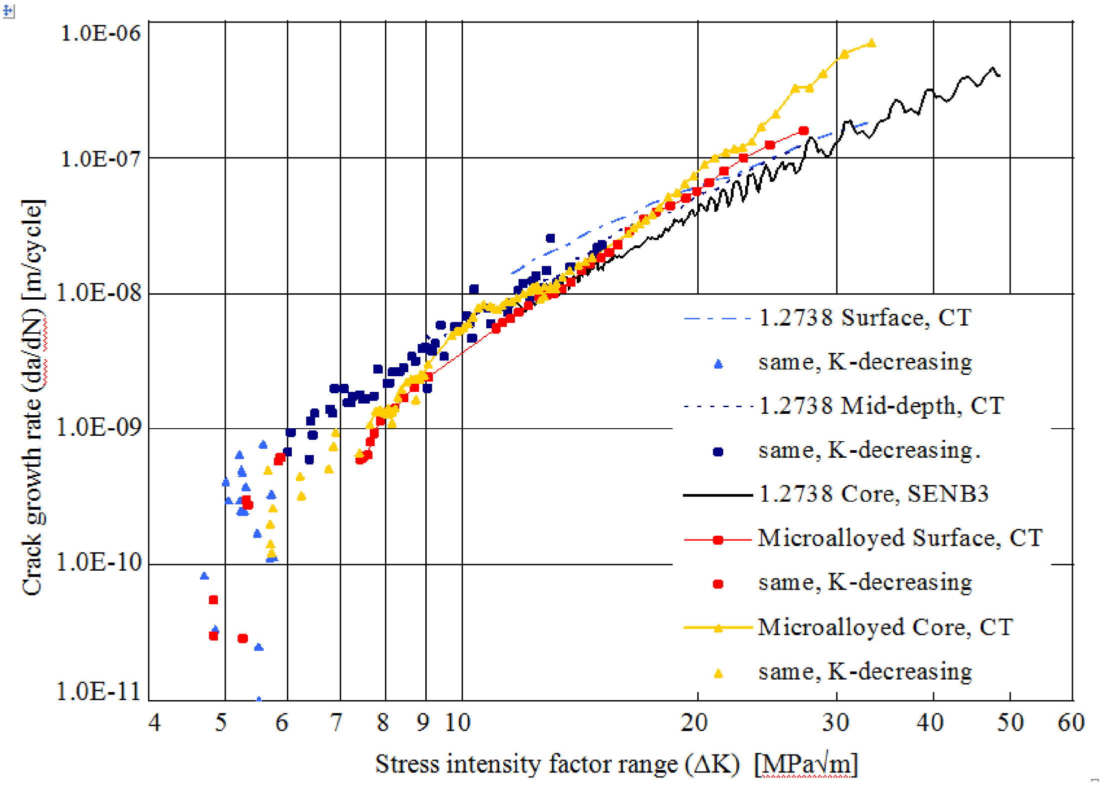


Figure 3. Microalloyed steel and steel 1.2738, different bloom positions. Paris plot of K-increasing or K-decreasing tests (lines or symbols) of SENB3 or CT samples.

rence between data pertaining to the two steels is hindered by the data dispersion.

S-N fatigue tests

The microalloyed steel showed a rotating bending fatigue stress limit (50% survival after 4.2×10^6 cycles) equal to 629±15 MPa at surface and 565±7 MPa at core, whereas the corresponding (previously determined [1]) values for the ISO 1.2738 steel are 559±17 and 493±19 MPa for the surface and core position, respectively.

Fractography

Fig. 4 and 5 reveal the fracture surface appearance after

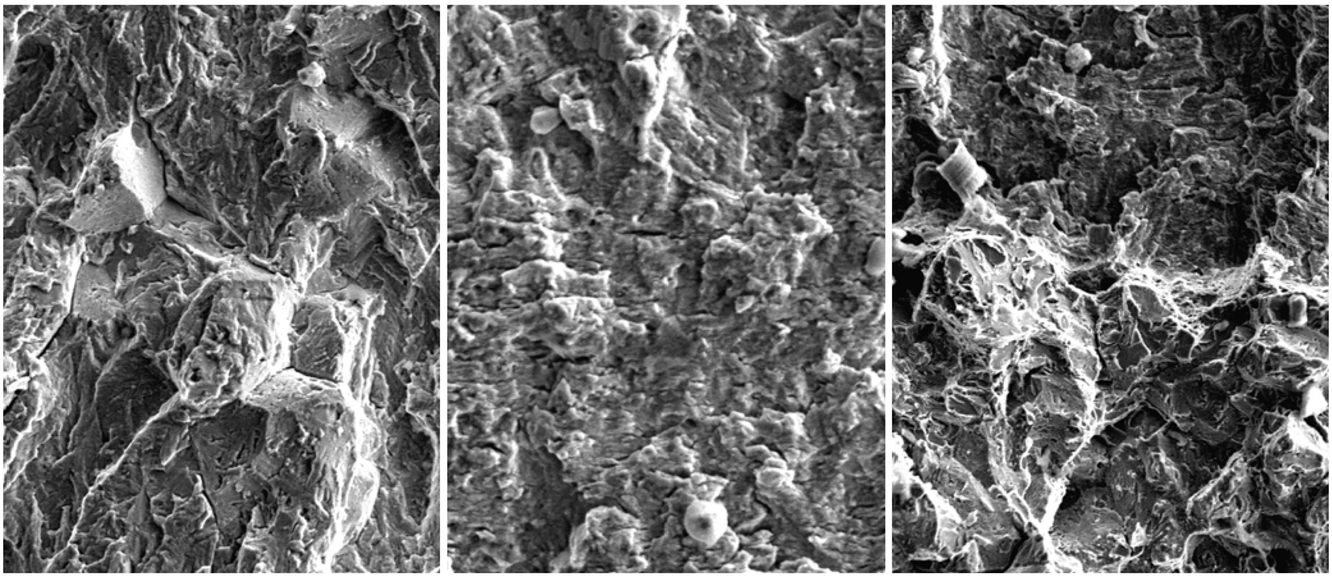
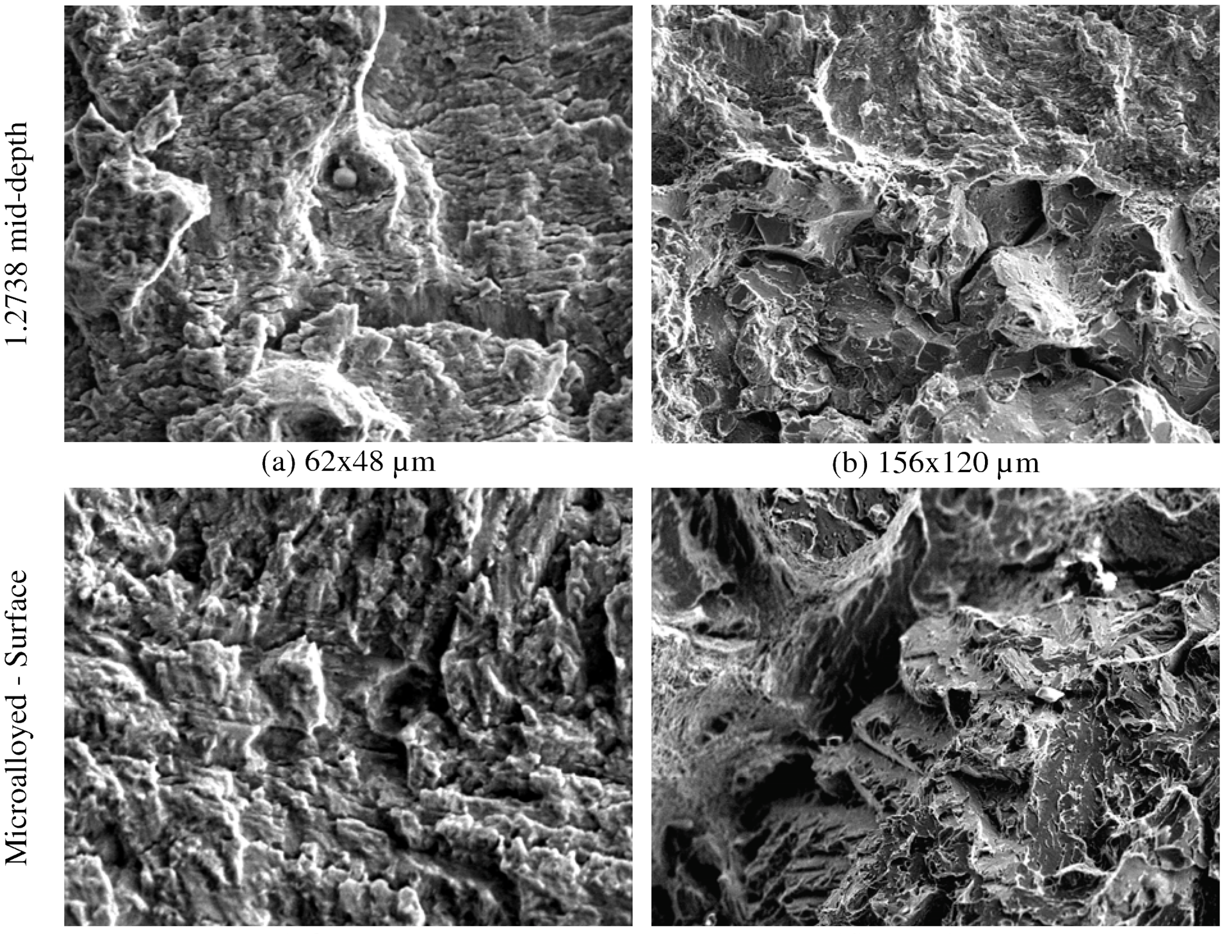

(a) 72x94 μm (b) 48x62 μm (c) 90x117 μm

Figure 4: Steel 1.2738, bloom surface position. Fatigue surface at da/dN ≈ 60 nm/cycle (a) and immediately before final fracture (b, c top); final fracture surface (c bottom). Crack propagates from top to bottom.



(a) 62x48 μm (b) 156x120 μm

(c) 62x48 μm (d) 234x180 μm

Figure 5: Steel 1.2738, bloom mid-depth position (a, b) and microalloyed steel, surface position (c, d): Fatigue surface at da/dN ≈ 140 nm/cycle (a), immediately before final fracture (b top, c); final fracture surface (b bottom, d). Crack propagates from top to bottom.

fatigue crack propagation at different bloom depth, in the Paris region (where steady state crack growth occurs), for both the steels.

The observed fatigue surfaces show sometime a small portion of intergranular fracture, occurring more frequently in the 1.2738 steel bloom surface specimen (Fig. 4a).

The fracture surfaces appearance of the final failure region (where unstable crack growth occurs) are reported in Fig. 4c, 5b and 5d. They all exhibit a brittle fracture with intermixed cleavage and intergranular rupture.

Fatigue striations are more evident at the highest ΔK values (occurring immediately before the rupture, due to the K-increasing procedure), such as in Fig. 4b, 5a and 5c.

4 DISCUSSION AND CONCLUSIONS

From the fatigue crack growth test results, it is understood that almost all as-received microstructures exhibit similar fatigue crack growth resistance. The fatigue crack growth exponent ranges from 3 to 4.

By comparing the FCG results of the individually re-heat-treated 1.2738 samples and of the as-received bloom samples, it is apparent that, at ΔK values larger than 20 MPa√m, the tempered martensite and the pearlite can be regarded as an upper and a lower bound, respectively, for the FCG rate of the varying microstructures inside a pre-hardened bloom. In this contest, the much steeper Paris curve of the bainite/martensite re-heat-treated sample is attributed to its untempered martensite content. Such behavior of this peculiar microstructure may explain the origin of cracks encountered at times in real molds modified in service by welds or weld bed depositions.

In the Paris law region, the FCG behavior of the bloom surface material, that consists mainly of tempered martensite, is very similar to that of the re-heat-treated tempered martensite sample, with the much smaller fracture toughness ($K_{Ic} \approx 35$ vs. ≈ 80 MPa√m [1]) justifying the lower limit of crack growth extension visible in Fig. 2. Moreover, the FCG rate of the re-heat-treated pearlite sample is smaller than that of the core sample, which consists only partially of pearlite (the rest being bainite). These results confirm that the FCG rate behavior of the 1.2738 steel is influenced by the micro-constituents, and that pearlite is more beneficial to the FCG performance than tempered martensite (even if the opposite holds for the fracture toughness [1]), since the former shows a FCG rate ~30% lower than the latter in the 20 to 50 MPa√m ΔK range.

Results concerning the rotating bending fatigue tests show that the microalloyed steel fatigue limit (50% survival after $4.2\text{x}10^6$ cycles) is somewhat larger than that of the traditional 1.2738 steel, and that its FCG rate is smaller than that of the 1.2738 steel up to ~ 20 MPa√m, but higher thereafter (since the overall Paris slope of the microalloyed steel is larger).

In the microalloyed steel case, the superior performance of the surface material in the S-N test can be justified by the smaller FCG rate observed at surface by comparing the surface and core Paris curves, particularly at the largest ΔK values. On the contrary, in the 1.2738 steel case, by increasing the distance from the original bloom surface, the overall FCG rate generally decreases (for a fixed ΔK); this result is apparently in contrast with the fatigue strength at $4.2\text{x}10^6$ cycles, previously assessed by S-N tests performed on smooth rotating bending specimens cut from the same bloom [1], that generally decrease from surface to core. Since the fatigue life of a smooth specimen consists first of short-crack nucleation and early growth and then of long-crack growth (only the latter being described by the Paris curve), it is concluded that the superior performance of the surface samples in the S-N tests, as opposed to the core ones, may stem from a longer time for crack nucleation, or lower rate of short-crack growth.

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