Fatigue crack propagation in new generation steels for plastic moulds

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ABSTRACT

One of the most common steels for plastic moulds is the ISO 1.2738 usually delivered after quench and tempering. The moulds are forged starting from an ingot and usually are heavy sized, being their dimensions up to 1m x 1m x 2m. It is well known that this can cause problems in terms of toughness, fatigue resistance and structural heterogeneity from surface to core. In order to improve these features, new pre-hardened non-standard materials have been developed recently. The aim of the study is to characterize the fatigue behaviour of these new generation steels using the fracture mechanics approach: crack propagation thresholds as well as stable and unstable crack growths have been investigated by measuring da/dN at increasing or decreasing ΔK's; the fracture surfaces have been observed by SEM microscope. Samples have been machined both from the surface and core materials of the original bloom. Moreover, a microstructural survey has been performed at different distances from the surface and the correlation with the local fatigue behaviour has been sought after.

INTRODUCTION

High hardenability steels, such as ISO 1.2738 (40CrMnNiMo8-6-4) are usually employed to produce moulds for large automotive components, made from reinforced thermoplastic polymers. Slightly less hardenable ISO 1.2311 steel is employed for smaller moulds.
Experimental investigations have shown that the steels, usually delivered as pre-hardened blooms characterized by heavy size dimensions (such as 1x1 m section, 1.5 m long), yield low toughness and impact absorbed energy (about 40 MPa√m and 10 J average, respectively) remarkably lower than those achieved in thinner samples. Moreover, continuously varying mixed microstructures (e.g. tempered martensite and bainite, or bainite and fine pearlite), with decreasing hardness and strength, occur from surface to core [1]. In order to improve these properties, new generation pre-hardened steels were proposed.
Since moulds are used to produce millions of pieces (corresponding to the production run of one car model), their fatigue behavior is relevant and a deep fatigue investigation is justified; in this paper Fatigue Crack Growth tests were performed in order to investigate both the threshold and the stable and unstable crack propagation. Moreover the fracture toughness was also determined. For the examined materials, both surface and core were investigated in order to study the effect of microstructure on toughness and fatigue properties.

MATERIALS AND METHODS

Two pre-hardened steels were investigated in terms of toughness by K_{IC} tests and in terms of fatigue behaviour by da/dN tests. The results were compared with a traditional mould steel, i.e. the ISO 1.2738. In Tables 1, 2 and 3 their chemical compositions are reported.

Tab.1. Chemical composition of ISO 1.2738.

	% C	% Cr	% Ni	% Mo	% Si	% Mn
% min	0,35	1,8	0,9	0,15	0,2	1,3
% max	0,45	2,1	1,2	0,25	0,4	1,6

Tab.2. Chemical composition of steel A.

	% C	% Cr	% Ni	% Mo	% Si	% Mn	% Nb	% Zr	% B
% min	0,2	1,2	0,9	0,4	0,1	1,3	0,01	0,02	0,001
% max	0,3	1,5	1,2	0,7	0,4	1,6	0,03	0,04	0,002

Tab.3. Chemical composition of steel B.

	% C	% Cr	% Ni	% Mo	% Si	% Mn
% min	0,2	1,2	0,9	0,4	0,1	1,3
% max	0,3	1,5	1,2	0,7	0,4	1,6

The steels were delivered as blooms with different dimensions: for ISO 1.2738 and steel A, the blooms sizes were respectively 1000 mm x 1000 mm (thickness) x 2000 mm and 1250 mm x 1000 mm (thickness) x 2900 mm, whereas steel B was smaller being its dimensions equal to 1240 mm x 300 mm (thickness) x 940mm. The heat treatment parameters are reported in Table 4.

Tab.4. As supplied conditions of the investigated steels

Steel	*Heat treatment*	*as – supplied hardness*
ISO 1.2738	Aqua - quench (from 850°C) and tempering	≅ 360 HB
A	Aqua - quench (from 950°C) and tempering	≅ 360 HB
B	Aqua - quench (from 900°C) and tempering	≅ 340 HB

In order to investigate the influence of microstructure on toughness and fatigue properties, samples were taken both from surface and core of the blooms and a microstructural survey was performed by light optical and scanning electronic microscopy.
The da/dN tests were performed both in the threshold and in the stable and unstable crack propagation fields according to the compliance method. For the threshold zone investigation, a ΔK decreasing technique was applied while the stable and unstable regions were studied by ΔK increasing. Both toughness and fatigue tests were carried out on three point bending specimens. After the da/dN tests, the fracture surfaces were observed by SEM examination and then by LOM in a plane perpendicular to the fracture surface.

RESULTS

The toughness tests were carried out on three point bending samples according to ASTM E 399-06 [2]. The specimens dimensions are reported in Table 5.

Tab.5. K_{IC} specimens dimensions

*thickness **B**[mm]*	*width **W** [mm]*	*length **L** [mm]*	*span **S** [mm]*	*notch **M** [mm]*
35	70	300	280	30

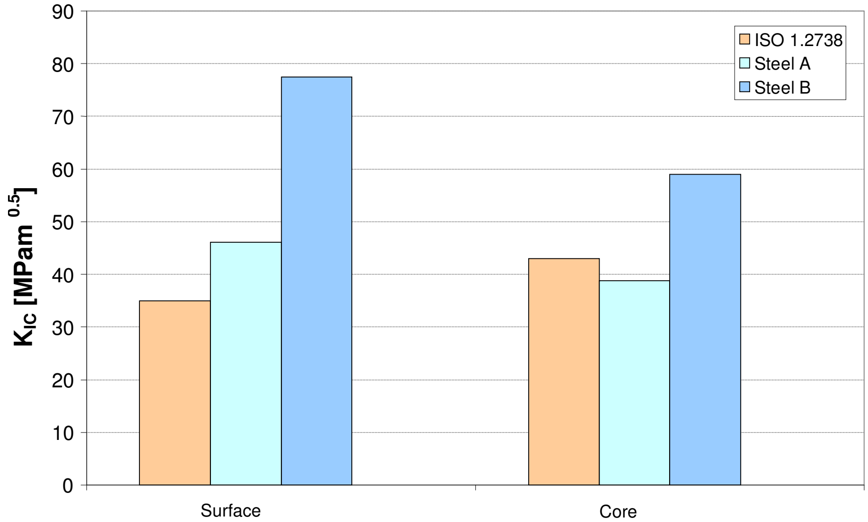

Fig.1. Toughness results for the investigated steels compared with ISO 1.2738.

Steel A, whose bloom size was comparable to the ISO 1.2738 one, showed slightly better toughness for surface samples, whereas for the core the values were very close. Steel B chemical composition is similar to steel A except for the micro-alloying elements. Its toughness was much higher probably because of the bloom thickness, about one third of bloom A. On such a bloom in fact, the heat treatment is more effective.

da/dN tests were performed aiming to investigate the whole Paris curve: both surface and core samples were considered. All the tests were carried out on three point bending tests according to ISO 12108 [3] for specimens dimensions and ASTM E 647-08 [4] for test procedure. The dimensions of the specimens are reported in Table 6.

Tab.6. da/dN specimens dimensions

*thickness **B**[mm]*	*width **W** [mm]*	*length **L** [mm]*	*span **S** [mm]*	*notch **M** [mm]*
15	30	70	60	5.6

Precracking was performed under load control: starting from an initial K value (K_{max}), the load decreases in order to give a final K (K_{min}), kept constant for a minimum crack propagation equal to 2.5% of the crack length itself. This method assures low deformation and strain-hardening at the notch tip. da/dN tests can be carried out according to two methods: the decreasing ΔK (decreasing the load) method and the increasing ΔK one (with constant load). In Figures 2 and 3, the data obtained from all the tests are reported.

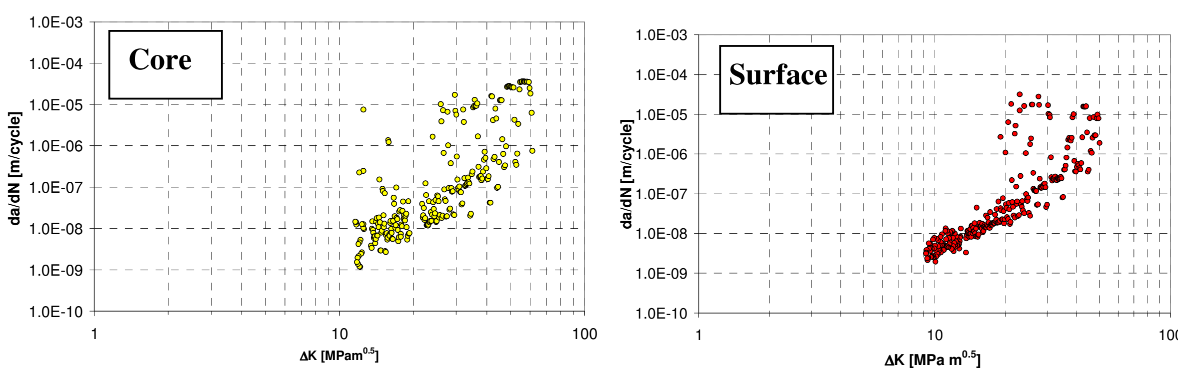

Fig.2. Paris curve for Steel A.

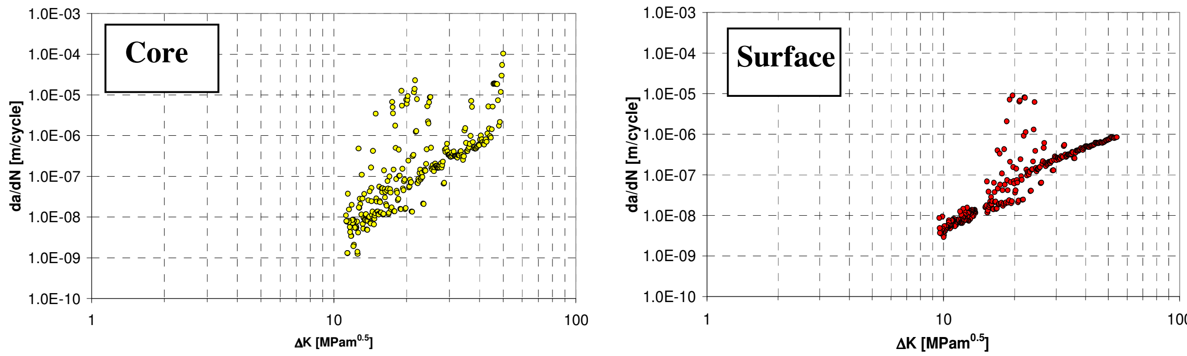

Fig.3. Paris curve for Steel B.

Most of the data are highly scattered. For a better understanding, SEM and LOM investigations were carried out and the crack path was observed along a plane perpendicular to the fracture surfaces. The two halves of the fractured surfaces were then matched, mounted, polished and etched in order to point out the influence of microstructure on crack propagation.
SEM observations were concentrated on steel A core sample, because it is the one with the largest level of scattering (Figure 4). The fracture surface didn't show evident marks of fatigue propagation, but cleavage-like features, suggesting that the propagation occurred prevalently by small successive brittle fracture steps rather than according to the common fatigue mechanisms of iterated crack tip blunting, deformation reversal and propagation in the strain hardened matrix.

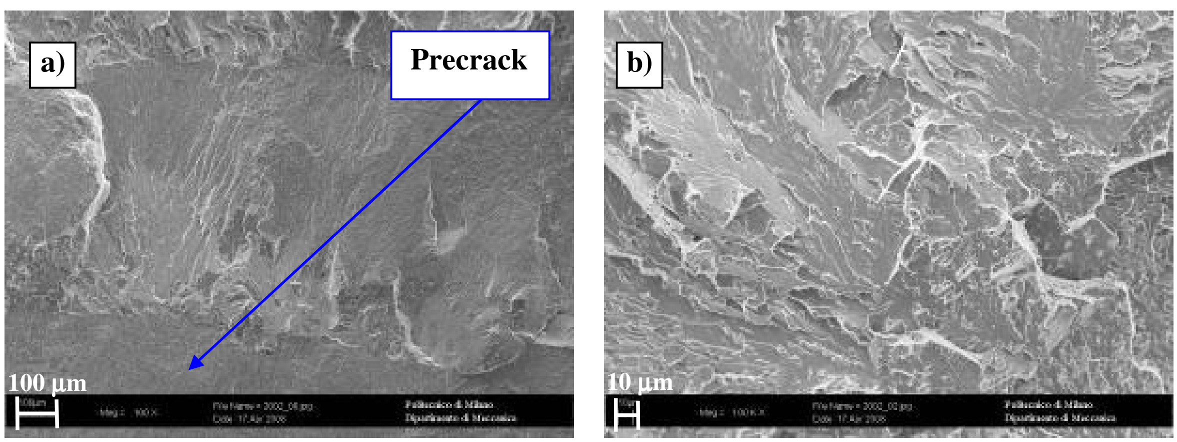

Fig.4. SEM images in the threshold zone (a) and in the stable crack propagation zone (b).

In previous experimental works a full microstructural investigation was performed on ISO 1.2738 finding mixed tempered martensite and temper modified bainite at surface and ferrite and pearlite at core [1]. In the following pictures a microstructural survey has been reported for steels A.

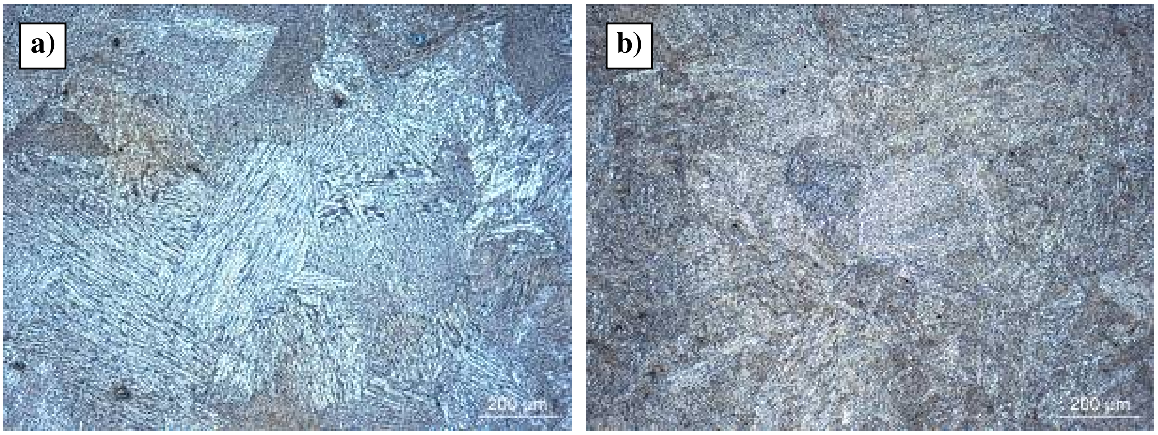

Fig.5. Microstructures observed in steel A at core (a) and in surface (b).

Both in steel A and B, the microstructure was prevalently temper modified bainite and tempered martensite. Nevertheless the microstructures are locally misoriented. These features surely affected the crack propagation and probably were responsible for the high data scattering. For supporting this hypothesis, the crack path was observed on etched core samples (Figures 6 and 7).

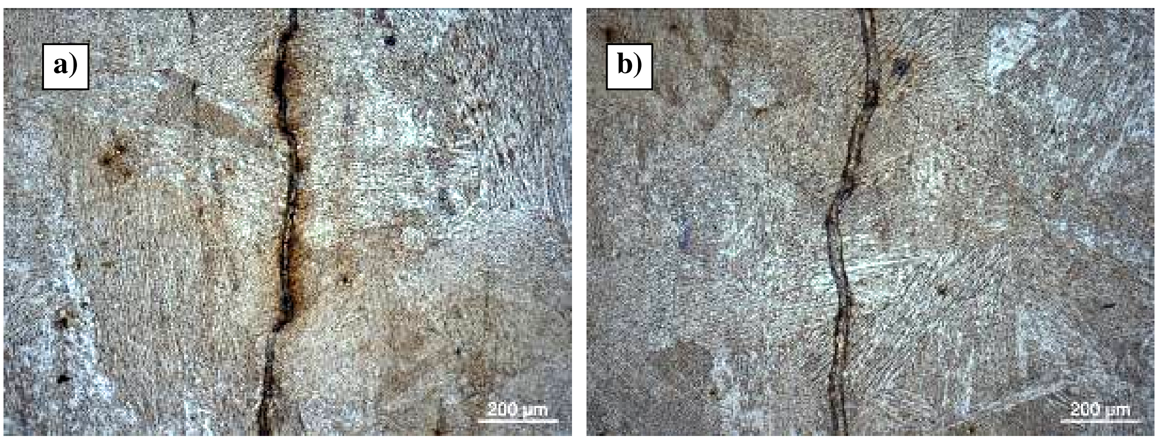

Fig.6. Crack path for steel A. Threshold zone (a) and stable propagation zone (b).

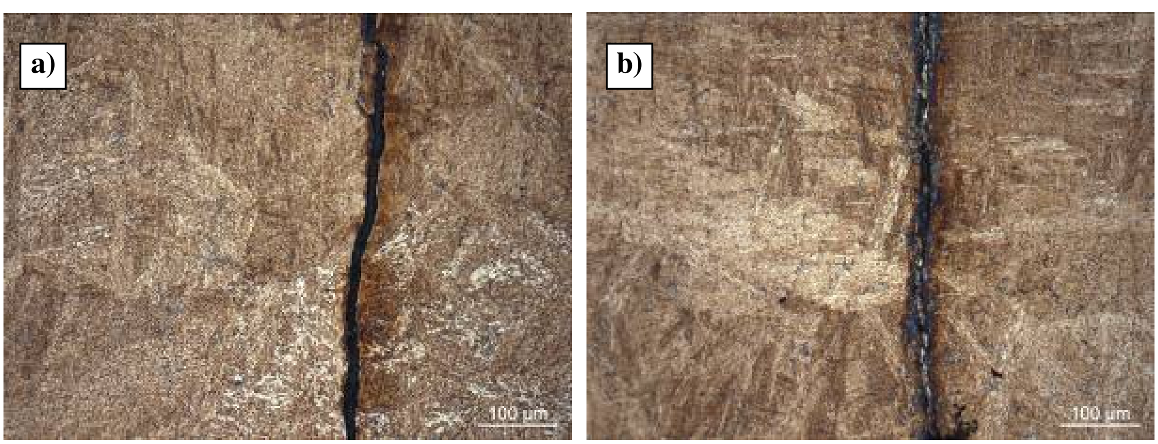

Fig.7. Crack path for steel B. Threshold zone (a) and stable propagation zone (b).

As observed in the microstructural investigation, in steels A and B macro-regions exist characterized by the same structures, but with strong local misorientation, that can be attributed to

not uniform forging operation. In steels A and B, the crack propagates through these regions and the values of the crack growth rate were obviously influenced.
Even if the curves were very scattered, we calculated the threshold values (Table 7) and the Paris law coefficients (Table 8) in the stable propagation field (included about between 10^{-8} and 10^{-6} m/cycle) comparing them with the ISO 1.2738 ones [5].

Tab.7. Threshold values

Steel	ΔK_{th} [MPam$^{0.5}$]
ISO 1.2738 - Core	8.4
ISO 1.2738 - Surface	8.9
A - Core	11.8
A - Surface	9.2
B - Core	11.4
B - Surface	9.6

Tab.8. Paris Law parameters

Steel	C	m
ISO 1.2738 - Core	$2\ 10^{-10}$	2.31
ISO 1.2738 - Surface	$6\ 10^{-12}$	2.91
A - Core	$4\ 10^{-14}$	4.76
A - Surface	$1\ 10^{-14}$	4.90
B - Core	$8\ 10^{-12}$	3.01
B - Surface	$1\ 10^{-11}$	3.04

For the investigated materials, the threshold values were slightly lower for the surface samples. Anyway steels A and B threshold values are larger than in ISO 1.2738. The latter, instead, shows the lowest m values, while for steel A this value was much higher, even almost 5.

CONCLUDING REMARKS

In this paper, two new generation steels were studied from toughness and fatigue points of view by determining both K_{IC} and da/dN variations (Paris Law) and comparing results with the reference ISO 1.2738 steel. On the basis of these results, the following conclusions can be drawn.

- Steel B showed the highest toughness. This behaviour could be due to a more effective heat treatment; its size, in fact, was about one third than bloom A and ISO 1.2738.
- The microstructure of steels A and B was prevalently bainite and tempered martensite with local misorientation.
- The crack propagation was influenced by such a microstructure thus resulting in highly scattered Paris curves.
- The threshold values of steels A and B were higher for core sample. Anyway, both surface and core thresholds were higher than the ISO 1.2738 ones.
- The Paris law exponent m was lowest for ISO 1.2738, whereas it increased up to about 5 for steel A.

REFERENCES

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