Semi High Speed Steels for Roughing Rolls with improved Thermal Fatigue Resistance

M. Pellizzari, A. Molinari, A. Biggi, G. Corbo, A. Tremea

Thermal fatigue represents one of the most significant causes for roughing mill roll deterioration and possible failure. The materials ability to withstand thermal cycling is strictly correlated to its microstructural properties, which are the result of the solidification process and following heat treatment. Rolls for hot strip rolling mills are usually produced by centrifugal casting, without subsequent forging. A crucial role is played by the eutectic carbide network developing on solidification, which represents a preferential pattern for crack propagation. For this reason conventional highly alloyed HSS are not a popular substitute for traditional Chromium steel rolls in rougher stands. The so - called "semi-HSS", containing less C (0.7-0.9 %C) and alloying elements are usually preferred by users requiring improved roll material. Specially developed "HSS for roughers" are being tested in various mills, but they are out of the scope of this paper. The present work is part of a continuing effort by INNSE Cilindri (RIVA Group) and Trento University to improve the "semi HSS" grades. In particular the thermal fatigue resistance of a new class of low-C semi HSS is evaluated. For purpose of comparison, both a conventional semi-HSS and a HSS grade were also considered. The test is based on induction heating (T_{max}=670°C) and water cooling of cylindrical discs. Experimental results confirm the lower susceptibility towards heat checking of the new grades, containing reduced amount of eutectic carbides, the best behaviour being exhibited by a steel with a mixed martensite-bainite matrix microstructure.

Parole chiave: thermal fatigue, semi-HSS, HSS, centrifugal casting, hot rolling, rolls, primary carbides

INTRODUCTION

Hot rolling represents a very important field of interest for the steel industry where big efforts are continuously made in order to respond to the ever increasing demand on product quality and low costs. To cope with this need, new process technologies and materials have been introduced. In the last decade the principal roll makers of the world devoted a lot of resources in the development of rolls with improved mechanical properties, wear and thermal fatigue resistance. Thermal fatigue represents the prominent cause of deterioration for the roughing rolls in hot strip rolling. These come into contact with the strip at the highest temperature (950°C and above) and are subsequently water cooled. The thermal dilatation of the heat affected region, less than 1mm thick, is partially constrained by the cooler subsurface so that thermal stresses cause the nucleation of cracks (heat checks) which negatively affect the surface smoothness. This is reflected in a bad finishing of the rolled strip and the mill must be stopped for rolls regrinding. This operation restores the initial defect-free surface of rolls but reduces their "real yield", expressed as rolled tons/mm of roll stock. Furthermore additional costs for the mill stop should be considered as a consequence of the poor thermal fatigue resistance. For these reasons the attainment of materials with improved properties represent an important goal for both roll makers and users.
For economical reasons centrifugal casting still represents a convenient technique for roll production. It overcomes the major problems of static casting, although segregation phenomena are typical for this process as well. Actually, semi high speed steels (semi-HSS in the rest of the paper) are becoming one of the preferred user options for roughing stands. In the early 90's they began replacing conventional Cr-steel [1]. Roughly, they can be defined as high speed steels with reduced C and reduced total alloying Cr + Mo + W + V, hence with reduced fraction of total carbides. The need to reduce the primary carbide volume percentage (CVP) is of major importance for spincasted rolls, since they are not subjected to forging after solidification and the primary carbides network represent a preferential path for thermal cracks [2-5]. The properties of the martensitic matrix, however, also give an important contribution to the thermal fatigue resistance of these products.
In this work the correlation between microstructure and pirocracking resistance of semi high speed steels is evaluated. A commercial grade is compared with six new compositions aimed at the reduction of CVP.

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MATERIALS AND HEAT TREATMENT

Eight different semi-HSS grades, identified by the suffix X in table I, were studied in this work. An HSS, identified by the suffix Y, was also included. Disc samples of 40mm external diameter and 10mm width were extracted by means of electro discharge machining from shell, produced by centrifugal casting in the productive plant of INNSE Cilindri, a well known italian roll maker belonging to the Riva Group. The standard semi-HSS steel, namely X0, contains about 0.7-0.9 %C and a quite high percent of Cr. The new grades can be distinguished for their lower C content, comprised between 0.5-0.8%wt and the decreasing amount in Cr and total alloying from X1 to X4. The idea is to lower the amount of primary carbides precipitating during solidification at the dendrite boundary and their interconnection as well. The indu-

strial practice and former laboratory tests evidenced that the interdendritic carbide network represents the preferential propagation path for thermal fatigue cracks, so that a beneficial effect could be expected for materials like X1 and X4. The relative high amount of alloying of X1, even higher than the standard grade X0, should be compensated by the relatively high content in Nb and V, which due to their strong ability in forming MC carbides, should promote a less interconnected precipitation. The principle is emphasized in the HSS grade Y0, by which the considerably higher C content is necessary to promote a strong precipitation of dissociated MC carbides [6] in presence of high %Nb+V. Semi-HSS X5 represent a variant of the standard X0 with minor addition of Cr and $W_{eq.}$ X6 and X7 represent a development of grade X5 with reduced C, Cr and W_{eq} aimed at the reduction of the total carbide volume percentage (CVP).
All the shells were quenched in forced air from 1030°C and double tempered at 500-520°C.

EXPERIMENTAL PROCEDURE

Metallographic samples were prepared by means of conventional paper grinding followed by polishing with 1mm diamond paste. Selective etching by Murakami's reagent (fig. 1) allowed to determine the amount of M_7C_3 and M_2C carbides, while the overall cabide volume percentage (CVP) was determined by etching the polished surface with Nital 5%. Quantitative image analysis was carried out using a Leica Q-Win software interfaced with the light optical microscope. At least ten fields were selected at 100X in order to achieve sufficient statistical reliability. Hardness and microhardness were also measured for each material.
Thermal fatigue tests were carried out by means of a self designed rig. The surface of the disc is induction heated up to 670°C and rapidly cooled down to 80°C by means of a water jet. More detailed information on the test is reported elsewhere [7]. As a consequence of the repetitive thermal cycling a certain number of cracks nucleate and propagate perpendicular to the disc surface, giving rise to the well known heat checking phenomena. The crack length was measured every 60 cycles for a total test duration of 180 cycles. The damage was quantitatively analyzed by means of four parameters: the crack density ρ (cracks/mm), the mean crack length l_m (µm) and the maximum crack length l_{max} (µm). The pirocracking factor P, given by the product of the former three parameters is considered as representative of the overall thermal cracking.

RESULTS AND DISCUSSION

The microstructural characteristics of the studied materials are summarized in table II. As expected semi-HSS always contains CVP lower than 5%, well below that of HSS Y0 which is about 10%. Very low CVP compared to X0 were measured for X2 and X3, due to the good combination of low C and alloying. M_7C_3 and MC carbide types only were revealed for all the steels investigated, the ratio MC/M_7C_3 being highest for HSS, presenting a large amount of globular MC. The dissociated morphology of these carbides has been just discussed previously [8] and can be ascribed to the ability of V and Nb to form primary precipitates at high temperature during solidification, when a consistent fraction of liquid phase is still present. MC can thus precipitate within eutectic cell instead of at dendrite boundary. The same phenomena cannot be observed in semi-HSS, where the lower amount in V+Nb allows the precipitation of a lower fraction of interdendritic MC. A peculiar chinese script morphology, different form the dissociated one, can be appreciated in

Steel grade	code	C	Cr	W_{eq}	V+Nb
Semi-HSS	X0	0.6-0.9	7.50	6.00	0.50
	X1	0.5-0.8	7.70	6.00	1.40
	X2	0.5-0.8	4.90	4.00	0.50
	X3	0.5-0.8	3.40	7.00	0.50
	X4	0.5-0.8	2.00	10.0	0.50
	X5	0.6-0.9	8.50	9.50	0.50
	X6	0.5-0.8	6.00	8.00	0.50
	X7	0.5-0.8	6.00	6.00	0.50
HSS	Y0	1.5-1.9	5.50	6.00	4.65

Table I – Nominal composition of the investigated materials (W_{eq}=W+2Mo).*

Tabella I – Composizione nominale dei materiali studiati (W_{eq}=W+2Mo).*

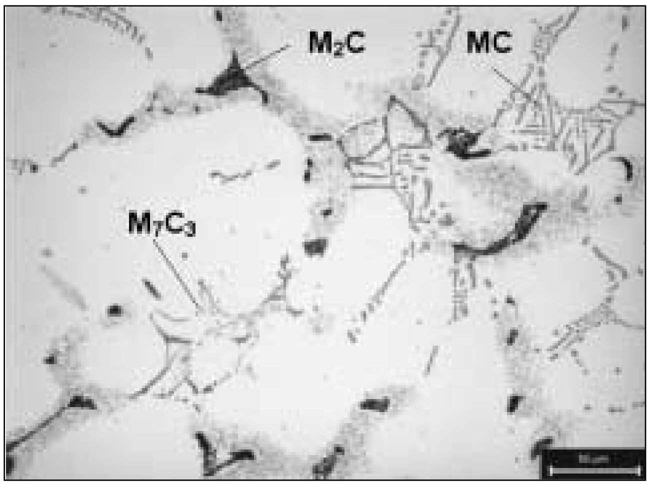

Fig. 1 – Steel microstructure after selective chemical etching (Murakamy's reagent).

Fig. 1 – Microstruttura dell'acciaio dopo attacco selettivo (reagente di Murakamy).

steel X1, the semi-HSS grade with the highest V+Nb. It is worth noting that, given constant %C and %V the amount of M_7C_3 does not increases by increasing Cr, indicating a known MC stabilizing effect of W and Mo [3]. Given the same heat treatment for all materials, X3 reaches very high microhardness, close to the standard X0, while X1 and X2 show remarkably lower values. An intermediate value is shown by X4.
A quite high CVP with respect to X0 is measured for X5, in accordance with the higher %C and alloying content of this steel. For the same reason, considerably lower CVP are present in X6 and X7 than in X5. The microhardness of X5 is the highest among the studied materials, X6 ad X7 also showing quite high values.

THERMAL FATIGUE TEST

The pirocracking factor P is reported in figure 2 versus the progressive number of thermal cycles. As a general rule HSS Y0 shows higher values than semi-HSS, the difference becoming more and more evident after the first test interval. The only exception is represented by X5 (Fig. 2b). Among the new semi-HSS:
- X1 is similar to the standard grade, apart from the initial damage (60 cycles) which is significantly higher;
- X4, X6 and X7 are better than the standard grade, in particular on increasing the number of cycles;
- X2 and X3 are much better than the standard grade.

Table II – Microstructural characteristics, HRC and HV0.1 of the investigated steels.

Tabella II – Caratteristiche microstrutturali, durezza HRC e microdurezza di matrice HV0.1 degli acciai studiati.

Code	Hardness		Microhardness		Volume Pct of Eutectic Carbides (CVP)				MC/M_7C_3
	HRC	sd	HV0.1	sd	MC	M_7C_3*	Tot	sd	
X0	59.0	0.6	702	7	0.6	2.2	2.8	0.70	0.27
X1	55.0	0.7	570	12	3.0	1.3	4.3	0.78	2.30
X2	55.8	1.1	584	17	1.1	1.0	2.1	0.83	1.10
X3	59.1	0.8	719	42	0.6	1.2	1.8	0.45	0.50
X4	54.2	0.3	654	23	1.0	2.5	3.5	0.21	0.40
X5	61.0	0.6	780	10	<0.5	5.1	5.1	0.45	≈0
X6	57.8	0.4	678	37	<0.5	2.4	2.4	0.05	≈0
X7	58.0	0.5	686	16	<0.5	2.1	2.1	0.34	≈0
Y0	58.4	0.5	702	15	7.0	2.8	9.8	0.42	2.50

* Includes M_2C carbides

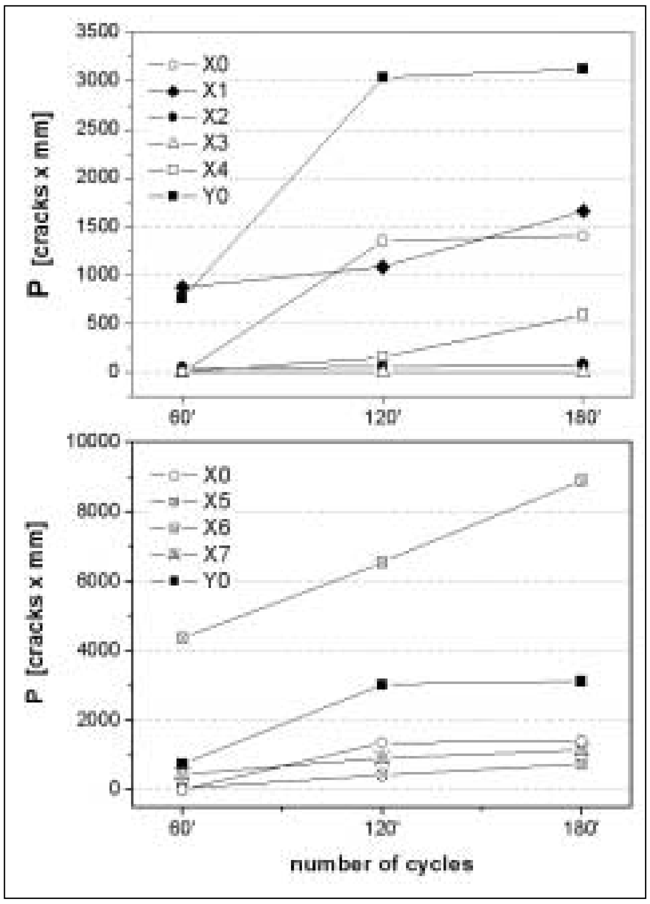

Fig. 2 – Evolution of the pirocracking factor during thermal cycling.

Fig. 2 – Evoluzione del fattore di pirocriccatura durante la prova di fatica termica .

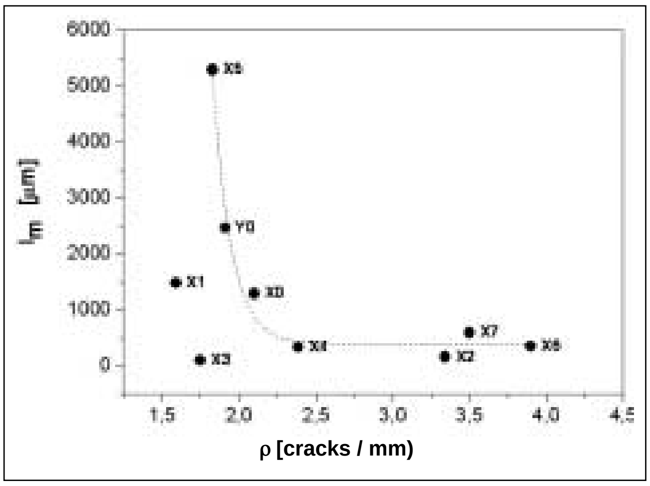

Fig. 3 – Mean crack length vs. crack density.

Fig. 3 – Lunghezza media l_m vs. densità di cricche ρ.

A more detailed interpretation of the pirocracking resistance of the studied steels, requires the three factors giving P, i.e., L_{max}, l_m and ρ, to be analyzed separately. As described in a previous work, for the steel classes studied the mean crack length l_{med} is inversely proportional to the crack density ρ. This relationship is graphically represented in Figure 3. The explanation can be found in the reduced local constraint in the vicinity of a long crack.

Here the material is rather free to deform during thermal cycling so that crack nucleation is strongly reduced in practice.

The experimental point related to the material with the best properties (X3) is located close to the origin.

The combination of low crack density and low mean length accounts for the very low P^{180} of this material. Moving form that point in figure 3, two different types of limit behaviour can be distinguished. A first type, represented by X2, X6 and X7 implies the nucleation of a high number of cracks with low mean length. The second type, represented by X5 or HSS Y0, implies high mean crack length and low density. From a technological point of view the first type has to be preferred, because of the lower grinding required to restore the initial roll finishing. Furthermore, long cracks are more critical with respect to other damage phenomena like surface fatigue.

Therefore, also X2 may be considered excellent, whereas X4, X6 and X7 give rise to higher P180 values due to the propagation of one very long crack, as will be shown later.

The above results can be correlated with the microstructure of the investigated steels.

Figure 4 highlights the influence of the carbide volume percentage (CVP) on the observed damage, expressed as the ratio between mean crack length and density l_m/ρ. By increasing CVP higher l_m/ρ are obtained, with minor exceptions, indicating an increasing propagation rate with respect to the nucleation one. Higher CVP usually means higher interconnection of the carbide network, so that thermal cracks propagate more easily. This result is confirmed by the increasing maximum crack length L_{max} observed by increasing CVP (Fig. 5).

The particular behaviour of X5 is confirmed by Figure 4: l_m/ρ is higher than expected on the basis of CVP. This could be attributed to the very high matrix microhardness which, combined to the higher CVP among semi-HSS may result in a very pronounced thermal fatigue damage [5,9].

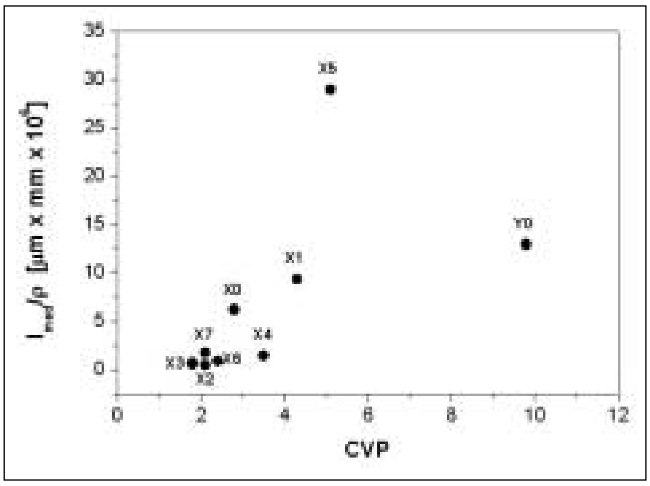

Fig. 4 – l_m/ρ vs. total carbide volume percentage CVP.

Fig. 4 – l_m/ρ vs. percentuale volumetrica di carburi CVP.

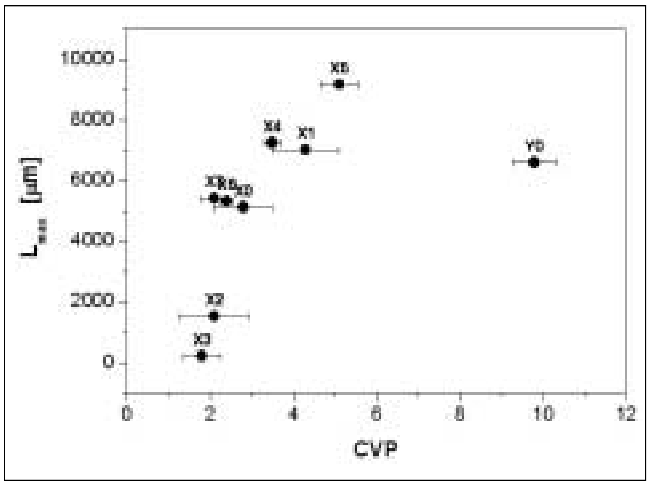

Fig. 5 – L_{max} vs. total carbide volume percentage CVP.

Fig. 5 – L_{max} vs. percentuale volumetrica di carburi CVP.

Figure 6 shows the pirocracking factor versus CVP; the trend is very similar to that in figure 4, indicating that the pirocracking factor is strongly influenced by the ratio between crack propagation and crack nucleation, and this, in turn, is mainly determined by the eutectic carbide volume percentage.

However, the carbide volume percentage is not the only parameter to influence the thermal fatigue properties of these steels. Both, figure 5 and figure 6 display some deviations from the general trend observed.

A very important role is played also by the matrix microhardness.

Thus in order to isolate the specific effect of CVP, we should compare the tribological behaviour of materials with similar microhardness. In table II, close HV0.1 values are reported for X0 and X3, the last one showing lower P due to its lower CVP. A similar conclusion can be drawn comparing X1 and X2.

The brittle propagation mechanism through the eutectic carbides is promoted by hard martensite microstructures. An exception is represented by X3 which shows very low P^{180} in correspondence of high microhardness. Microstructural investigation allowed to ascribe the excellent properties of this material to a particular mixed microstructure of martensite and bainite . This last constituent impairs higher toughness to the matrix which results more efficient in promoting crack arrest.

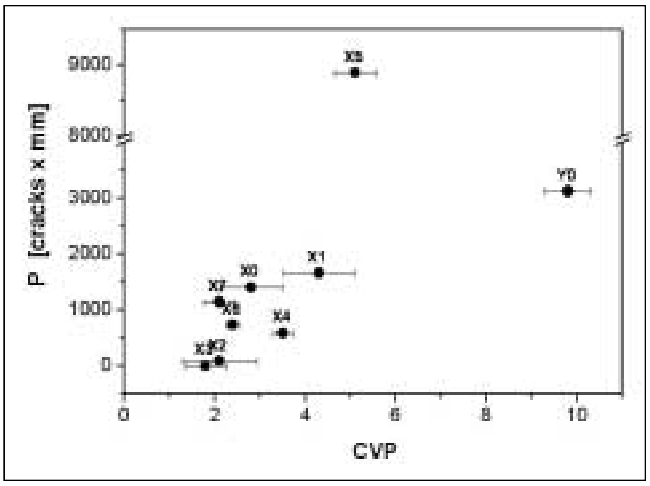

Fig. 6 – P vs. total carbide volume percentage CVP.

Fig. 6 – P vs. percentuale volumetrica di carburi CVP.

CONCLUSIONS

In this study the thermal fatigue resistance of semi high speed steels was correlated to their microstructure. A series of new grades, characterized by relatively low %C and alloying elements, was compared to a commercial standard steel, namely X0. The new compositions were tailored to study the effect due to primary carbides percentage and interconnection. The carbide volume percentage (CVP) was comprised between 1 and 5% for the steels evaluated. For purpose of comparison a HSS, containing about 10% carbides was also considered.

Eutectic carbides, mostly M_7C_3 with minor content in MC, are segregated to the cell boundaries. Their level of interconnection increases with increasing amount of carbides. Thermal cracks nucleate at the carbide/matrix interface and even inside carbide. Crack propagation follows. The results, expressed by the mean crack length l_m, the maximum crack length L_{max}. the crack density r and the pyrocracking factor P (l_m x L_{max} x ρ) can be summarized as follows:

- The pyrocracking factor P^{180} at the end of the 180 cycles, is higher for materials presenting high mean crack length l_m and maximum crack length L_{max};
- P^{180} increases by increasing CVP: mean crack length l_m and maximum crack length L_{max}, in particular, increase with increasing CVP;
- An inverse relationship exists between mean crack length l_m and crack density ρ;
- High matrix microhardness reduces the thermal fatigue resistance of semi-HSS reducing the steel toughness.

Among the new rolls compositions X3 shows the best thermal fatigue resistance due to a very low CVP and a mixed martensite-bainite matrix microstucture. This material exhibits the best combination of low l_m and ρ and the lowest P as well. The high microhardness of this material is compensated by the toughening effect of bainite.

Good properties were also exhibited by X2, X6 and X7 showing low l_m but considerably higher r than X3.

All the steels show improved thermal fatigue resistance than the standard X0 whit exception of X5, the hardness of which, in combination with the high CVP, abruptly compromised its fracture toughness and X1, with relative low hardness but high CVP.

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A B S T R A C T

ACCIAI SEMI-RAPIDI PER CILINDRI SBOZZATORI CON MIGLIORATA RESISTENZA ALLA FATICA TERMICA

Parole chiave: acciaio, lavorazioni plastiche a caldo, fatica, metallografia, impieghi alta temperatura

La fatica termica rappresenta una delle più importanti cause di danneggiamento e possibile rottura per i cilindri sbozzatori. La resistenza del materiale ai continui cicli termici risulta strettamente correlata alle sue proprietà microstrutturali, che sono il risultato del processo di solidificazione e successivo trattamento termico. I cilindri vengono generalmente prodotti per colata centrifuga, senza ulteriore forgiatura. Un ruolo decisivo è così costituito dalla maglia di carburi primari che precipitano durante la solidificazione e che rappresentano il percorso preferenziale per la propagazione delle cricche di fatica termica. Per questa ragione gli acciai rapidi non hanno soppiantato gli acciai al cromo tradizionalmente impiegati nelle gabbie sbozzatrici. Da tutti quegli utilizzatori che richiedevano cilindri a prestazioni migliorate sono stati loro preferiti i cosiddetti acciai semi-rapidi, a ridotto tenore di C (0.7-0.9 %C) ed elementi in lega,. Speciali "acciai rapidi per gli sbozzatori" sono stati provati in diversi impianti, ma esulano dallo studio qui proposto. Il presente lavoro è il risultato dello sforzo continuo che INNSE Cilindri (Gruppo RIVA) ed Università di Trento hanno compiuto negli ultimi anni per lo sviluppo di acciai semi-rapidi. Si è valutata in particolare la resistenza alla fatica termica di una nuova classe di acciai semi-rapidi a basso C (denominati X1-X4). A titolo comparativo si sono considerati anche un acciaio semi-rapido convenzionale (X0), un acciaio rapido (Y0), e tre acciai semi-rapidi sperimentali della "prima generazione" (X5-X7). I test eseguiti si basano sul riscaldamento ad induzione (670°C) e raffreddamento in acqua di dischi cilindrici.

L'analisi metallografica evidenzia un tenore di carburi compreso fra 1 e 5% per i nuovi acciai, decisamente inferiore a quello dell'acciaio rapido (10%). I carburi, prevalentemente del tipo M_7C_3, con presenze minori di MC, sono segregati ai bordi delle celle eutettiche. Il loro livello di interconnessione aumenta all'aumentare della percentuale volumetrica. Le cricche di fatica termica nucleano all'interfaccia carburo-matrice ed anche all'interno dei carburi stessi. La propagazione avviene prevalentemente lungo i carburi.

I risultati delle prove di fatica termica, espressi attraverso la lunghezza media l_m, la lunghezza massima L_{max}, la densità di cricche ρ ed il fattore di pirocriccatura P (l_m x L_{max} x ρ), possono essere riassunti nei punti seguenti:

- *il fattore di pirocriccatura P^{180} al termine dei 180 cicli, è più elevata nei materiali che presentano elevate lunghezza media l_m e lunghezza massima L_{max} di cricca;*
- *P^{180} aumenta all'aumentare della percentuale volumetrica di carburi primari (CVP): in particolare, lunghezza media l_m e lunghezza massima L_{max} aumentano all'aumentare di CVP;*
- *la lunghezza media l_m aumenta al diminuire della densità di cricche ρ;*
- *l'eccessiva microdurezza di matrice reduce la resistenza alla fatica termica degli acciai semi-rapidi, producendo un calo drastico della loro tenacità.*

In generale i risultati confermano la minor suscettibilità alla pirocriccatura delle nuove analisi a ridotto contenuto di carburi ed evidenziano il miglior comportamento per l'acciaio che presenta una microstruttura di matrice mista, composta da martensite e bainite (X3). Questo materiale evidenzia la miglior combinazione di l_m and ρ ed il minor danneggiamento complessivo P. L'elevata microdurezza che gli compete è compensata dall'effetto tenacizzante della bainite. Buone proprietà sono evidenziate anche da X2, X6 ed X7, che mostrano bassa l_m ma ρ considerevolmente più elevate. Tutti questi acciai risultano migliori dello standard X0, ad eccezione di X5, la cui durezza, in combinazione alla CVP relativamente alta, ne compromette la tenacità a frattura ed X1, con durezza relativamente bassa ma elevata CVP.