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An alternative to TempCore®: Dual-Phase reinforcing steels. Mechanical characterization and durability performance

Silvia Caprili[a], Walter Salvatore[a], Renzo Valentini[a], Cristiano Ascanio[b], Gianbruno Luvarà[b]
[a] *Dipartimento di Ingegneria Civile e Industriale, University di Pisa, Largo L. Lazzarino 1, 56122 Pisa, Italy*
[b] *Ferriere Nord S.p.A., Zona Industriale Rivoli di Osoppo, 33010 Osoppo, Udine, Italy*

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ABSTRACT

Dual-Phase (DP) steel reinforcing bars represent a valid alternative to TempCore® grades, being characterized by comparable values of strength and deformation capacity and, besides, by improved durability thanks to the typical microstructure in which the martensite phase – main responsible for corrosion – is not 'external' but 'embedded' in the ductile ferrite matrix. Actually, Dual-Phase grades are used for flat products (like sheets or plates) and normally produced in batch process by the application of an additional intercritical quenching thermal cycle able to guarantee the desired microstructure. The Authors deeply analyzed the possibility to produce Dual-Phase steel reinforcing bars without the need to strongly modify actual plants for reinforcing steel; a specific thermal cycle, consisting of an intercritical quenching followed by a rapid cooling stage applied to pre-selected chemical compositions allowed to achieve the desired microstructure. In the present work, the summary of the results of the whole mechanical characterization performed on DP steel rebars is presented in reference and corroded conditions, in comparison to traditional TempCore® B450C. Monotonic and cyclic experimental tests were performed to represent the effective situation of reinforcements in modern reinforced concrete constructions.

1 INTRODUCTION

Dual-Phase (DP) steels are nowadays widely used in the automotive sector due to their excellent performance in terms of both strength and deformation capacity. DP grades can reach strength levels up to 1000 MPa (this is the case, for example, of DP1000) in relation to the percentage of the different components' amounts; the main responsible for the mechanical properties are, as well known, *Carbon* (C), *Manganese* (Mn) and *Silicium* (Si), whose percentages highly influence both strength and ductility.

From the microstructural point of view, DP steels are characterized by a '*mixed microstructure*' in which the martensite phase is directly embedded in a ductile ferrite matrix, making the resulting product not significantly affected by durability problems mainly related to the presence of martensite. Nowadays, DP steels are produced mainly in *flat* products (sheets, plates) while their application to the field of construction engineering, and in particular, the application for reinforced concrete (RC) constructions by means of steel reinforcing bars (rebars) is limited due to two different main aspects. First of all, actually, the production process needed to achieve Dual-Phase rebars is not well-validated and consequently the use of actual steel plants for reinforcements to gain DP rebars is not easy and results are limited to few scientific attempts. Secondly, the costs related to the production process are high, requiring a strong economic effort from steel producers and a very conditioned applicability to the 'poor' sector of RC constructions.

But why the employment of Dual-Phase steel reinforcing bars can be useful for constructions? The motivation can be found in the durability performance of this typology of material. As said, DP steels present a microstructure in which the relatively low percentage of martensite is enclosed in the ferrite matrix, being then not directly exposed to external environment like in the case of TempCore® steel reinforcing bars, nowadays the most diffused typology of reinforcements used for RC constructions.

The TempCore® process, characterized by the two following phases of quenching and tempering developed from the 1970s, allows to achieve a product characterized by good performance in terms of strength (both yielding and ultimate R_e, R_m), deformation capacity ($A_{gt}; A_5; R_m/R_e$) and weldability towards moderate production costs. The production process, otherwise, leads to the development of a dual-microstructure characterized by the presence of a ductile ferritic core (providing good deformation capacity) and an external harder martensitic layer responsible for the good strength performance.

The martensite layer is, otherwise, responsible for the bad durability aspects of the material: recent studies in the current scientific literature (Caprili and Salvatore 2015; Caprili et al. 2015; Imperatore et al. 2017) highlighted the poor quality of TempCore® steel reinforcing bars in presence of aggressive environmental conditions causing corrosion, both due to carbonation or to chlorides' attack, with relevant decrease of the deformation capacity to values even lower than the requirements imposed by actual standards for RC constructions (NTC2018; EN1998-1:2005).

According to national and international codes, steel reinforcing bars shall be provided by adequate deformation capacity expressed in terms of elongation to maximum load (A_{gt}) and hardening ratio (R_m/R_e) that, for buildings realized in Ductility Class High (DCH) shall not be lower than, respectively, 7.5% and 1.15 (this last one also not higher than 1.35). In presence of corrosion (and in relation to the corresponding mass loss percentage – considered as the main relevant indicator for uniform/carbonation corrosion condition) the deformation capacity can be even lower than 5.0%. This contrasts with what highlighted by recent studies (Braconi et al. 2014) that evidenced deformation demand imposed by a generic seismic event to modern RC buildings, even up to 9%.

Consequently, the interest in the realization of an enhanced typology of steel reinforcing bars with Dual-Phase microstructure – then provided by mechanical performance comparable to the ones achieved with TempCore® grades and by improved durability – arises during the last years (Maffei et al. 2007; Salvatore et al. 2007).

In the present paper the work developed to achieve DP steel rebars through a production process characterized by the application of a well-defined thermal cycle is presented, together with the following characterization of the achieved product in both reference (uncorroded) and corroded conditions.

The work has been developed in the main framework of the European research project NEWREBAR "*New Dual-Phase steel reinforcing bars for enhancing capacity and durability of antiseismic moment resisting frames*" (2015-2019), funded by the Research Fund for Coal and Steel (RFSR-CT-2015-00023) of European Commission.

2 PRODUCTION OF DP REBARS

2.1 Definition of the production process

Nowadays two ways exist for the achievement of a 'real' Dual-Phase microstructure. The first one consists in the application of a continuous hot-rolling process, but, in general, only few grades (e.g. DP800) are obtained by this method. On the other hand, more frequently, DP microstructure is achieved through the application of a *post-process* consisting in an additional Intercritical Quenching (IQ) treatment: a first hearing stage within the intercritical region (740°C-820°C) followed by a rapid cooling stage (Salvatore et al. 2007; Caprili et al. 2018; Sarkar et al. 2005) are able to provide DP characteristics.

The resulting mechanical performance of the achieved products are function of the morphological features of the microstructure, of the ratio ferrite/martensite and of the process parameters (e.g. the annealing temperature, the velocity of the process, the presence of additional alloy elements, etc.). The martensite amount, is, besides, strictly connected to the resulting mechanical and durability performance: the higher is the martensite percentage the higher is the resulting strength, but, at the same time, the higher is the tendency to corrosion and to the following ductility decrease (Sarkar et al. 2005; Trejo et al. 1994; Keleştemur and Yıldız 2009).

Since the application of a production process completely different from the one actually adopted for reinforcing steel (i.e. quenching and tempering) would highly increase the costs of the resulting product, first attempts were made (Caprili et al. 2018) to 'modify' the microstructure of TempCore® reinforcements by applying an additional IQ step with temperature and velocity opportunely simulated through numerical calculations. As already presented by Caprili et al. (2018), the results were not satisfactory in terms of durability properties, since the external martensite layer was 'deleted' only through the application of a pre-annealing treatment with temperatures of about 1000°C, with the following increase of the grain size of steel and the decrease of the resulting mechanical performance (e.g. strength values lower than 300 MPa, not applicable to RC constructions).

The final production process adopted for Dual-Phase steel reinforcing bars in the following tests then accounted for the three following phases. The first necessary step is the determination of optimal chemical composition ranges of main components (C, Mn, Si, etc.) and of the optimal IQ temperature for the achievement of DP microstructure characterized by the lowest martensite amount (but keeping the resulting level of strength competitive with actual requirements for reinforcing steels). Several simulations were performed using *ThermoCalc*® software to determine the resulting state diagrams and to consequently estimate the microstructural and mechanical performance.

The second step of the process consisted in the application of the thermal cycle including, as simply schematized in Figure 1, a first heating stage in the range 730°C-780°C and an additional tempering step (600°C) to increase ductility performance.

The thermal cycle was applied to jumbo coils of diameter 16 mm (1200 kg each) produced by Ferriere Nord S.p.A plant (Italy) using components' ranges opportunely identified and summarized in Table 1. After the treatment the coil was finally straightened achieving steel reinforcing bars of adequate length (up to 6000 mm as used for constructions).

All the process was applied through the help of an industrial Italian thermal treater (TTN)

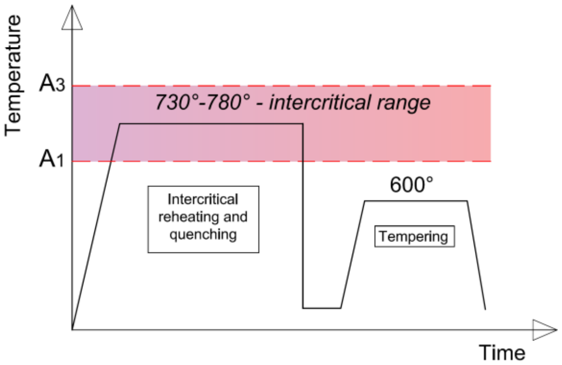


Figure 1. Thermal cycle for IQ treatment of produced coils.

2.2 *Achieved product and microstructural characteristics*

Two different chemical composition ranges (in the following defined DPD and DPF, to distinguish) were selected after preliminary simulations and practical laboratory attempts as presented in Caprili et al. (2018) for the industrial production of coils and for the following application of IQ treatment, achieving DP microstructure. For sake of comparison, and with the aim to assess the benefit of DP grades respect to TempCore®, steel grade B450C was also subjected to mechanical characterization. Table 1 summarizes the different chemical compositions of the casts realized to produce both DP and ordinary reinforcing steels. As visible, the C-amount of grades DPD and B450C is the same (equal to 0.233%), while DPF presents a lower amount (equal to 0.160) being then very promising concerning durability performance. The analysis of martensite/ferrite ratio evidences the lowest values of martensite in case of DPF (Figure 2)

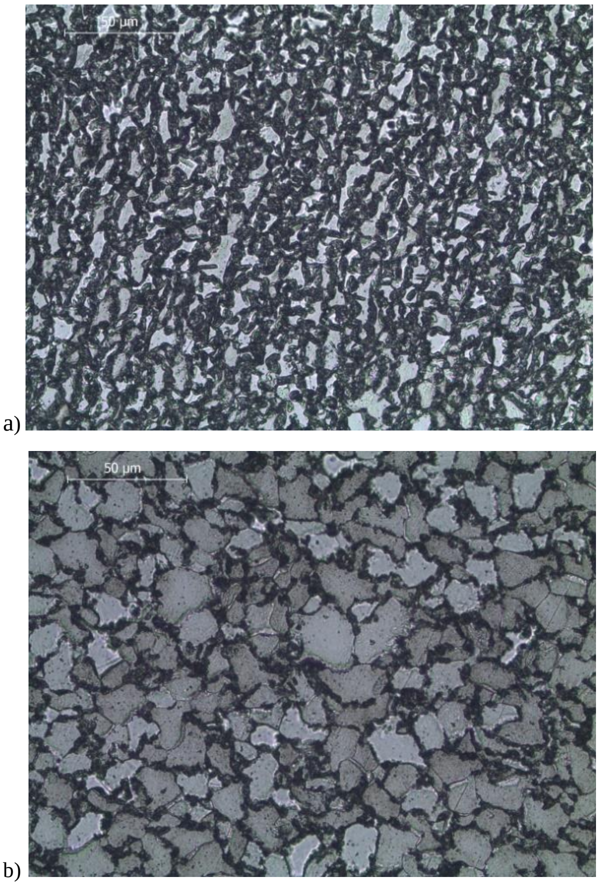


Figure 2. Martensite (black) and ferrite contents after different IQ temperatures. a) DPD, IQ 740°C; b) DPF, IQ 760C (Caprili et al. 2019).

Table 1. Components' amount for the different steel grades considered (all the values are expressed in percentage - %)

DPD	C	Mn	Si	P	S	Cu
	0.233	1.253	0.178	0.0296	0.0095	0.353
	N	Cr	Ni	Mo	C_{eq}	
	0.009	0.131	0.158	0.0381	0.510	
DPF	C	Mn	Si	P	S	Cu
	0.160	0.999	0.166	0.0303	0.0099	0.372
	N	Cr	Ni	Mo	C_{eq}	
	0.0118	0.166	0.137	0.0303	0.400	
B450C	C	Mn	Si	P	S	Cu
	0.233	0.646	0.138	0.0184	0.0422	0.371
	N	Cr	Ni	Mo	C_{eq}	
	0.0117	0.0801	0.113	0.0187	0.393	

3 MECHANICAL CHARACTERIZATION OF DP REBARS

3.1 *Performance in reference/uncorroded conditions*

The mechanical performance of Dual-Phase steel reinforcing bars (and of TempCore® B450C for sake of comparison) were assessed under both monotonic tensile and Low-Cycle Fatigue (LCF) loading conditions, representing the typical situations to which reinforcements are subjected in ordinary RC constructions. LCF tests (i.e. cyclic tests performed for few cycles of high imposed deformation) were used to assess the behaviour under seismic action. Specimens of diameter 16 mm – being one of the most representative for RC constructions – were produced and tested.

For the monotonic tensile tests, EN15630-1:2010 was followed; at least five specimens were tested for each steel material (DPF, DPD and B450C) to have sufficient data to stabilize the results. In case of DPD, due to the variability of results achieved, eight tensile tests were executed. Of course, since the high-temperature cycle was applied to a jumbo coil with a specific thickness, the effects of the IQ thermal treatment were not exactly the same in all the specimens extracted, even if variations were limited with an accurate preparation of samples.

Tests were performed at the *"Laboratorio Ufficiale per le Esperienze sui Materiali da Costruzione"* of Pisa University using a force-control machine; an average stress-rate equal to $10\ MPa \cdot s^{-1}$ in the elastic field, respecting limits of EN ISO 6892-1:2009 was used. Results are summarized in Table 2, in terms of yielding and tensile strength (R_e, $R_{p,02}$ for not defined yielding curves, R_m), elongation to maximum load (A_{gt}), ultimate elongation (A_5), hardening ratio and necking (Z). All stress values presented refer to the bar's diameter evaluated basing on measures of length and weight of each single rebar (note that necking phenomena in the softening range have been neglected). In the present work, only average results are presented while more details and information can be found in Caprili et al. (2019).

Figure 3 shows the stress-strain diagrams achieved by positioning two displacement transducers along the specimen during the test; small variations can be appreciated by comparing the data presented in Table 2 (coming from *manual* measurements) and the diagrams (mainly in terms of deformation), especially in the post-peak phase. Such differences are due to relative slip of the transducers along the bar during the necking phase.

Table 2. Average values of monotonic tensile tests results for the different typologies of steel reinforcing bars.

Steel type	R_e $R_{p,02}$ (MPa)	R_m (MPa)	R_m/R_e (-)	A_{gt} (%)	A_5 (%)	Z (%)
DPF	403.6	525.1	1.30	13.9	31.5	51.1
DPD	460.7	590.6	1.28	11.9	26.1	52.1
B450C	485.7	594.8	1.22	15.7	26.7	42.3

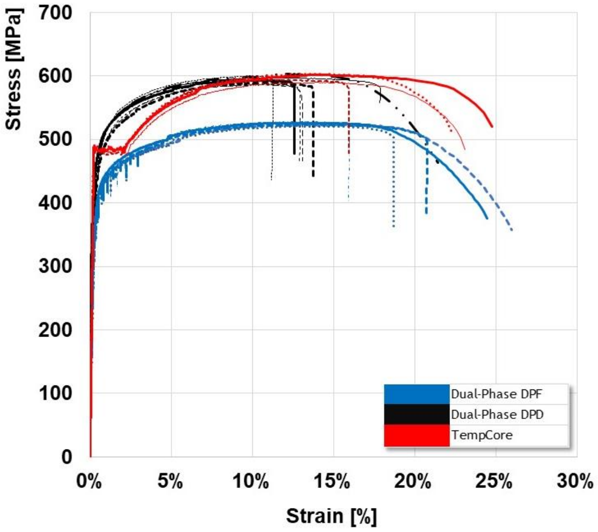
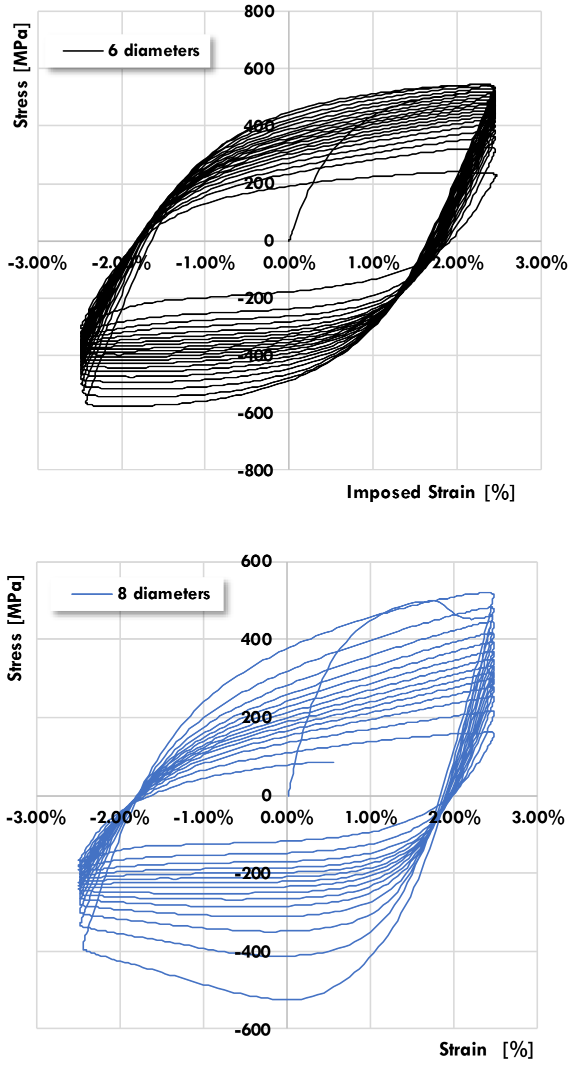


Figure 3. Stress-strain curves coming from tensile tests *(measures are taken from transducers positioned on the rebars).*

As visible, the mechanical performance of DPD and B450C were comparable in terms of strength (average values of yielding respectively equal to 460 MPa and 485 MPa), while DPD showed lower deformation capacity (11.9% of A_{gt} vs 15.7%). On the other hand, the higher deformation capacity of DPF (13.9% of A_{gt}) was associated to lower strength values, both ultimate and yielding. It is otherwise to be underlined that the deformation capacity of the provided TempCore® steel was widely higher than what tested in other context (see for example Caprili et al. 2015), towards lower strength. In any case, tests showed that produced DP grades are compatible with European requirements for reinforcing steels.

Concerning the cyclic performance, LCF tests were executed following the protocol presented in Caprili and Salvatore (2015), consisting in the application of different levels of imposed deformation (±1.0%, ±2.5%, ±3.0% and ±4.0%), with testing frequency up to 2.0 Hz (frequently reduced due to machine's requirements) to two different buckling length of the specimens (L_0), respectively equal to 6 and 8 diameters. For each testing condition (deformation/free length) and for each steel grade (DPD, DPF and B450C) at least three LCF were performed.

Figure 4 shows the typical cyclic stress-strain diagrams achieved for DPF specimens; Table 3 shows the average results of cyclic tests, presented in terms of average number of cycles to failure (N_{cycles}) and total dissipated energy (dE).



a)

b)

Figure 4. Stress-strain cyclic diagram achieved from LCF tests on DPF rebars for imposed deformation ±2.5% and buckling length equal to a) 6 diameters; b) 8 diameters.

Table 3. Average results of LCF tests on DP and TempCore® rebars (Caprili et al. 2019).

L_0	Δε	Av. dE (MPa)			Av. N_{cycles} (-)		
		DPF	DPD	B450C	DPF	DPD	B450C
6ϕ	±1.0%	1795	1423	1811	330	254	347
	±2.5%	720	500	625	33	21	26
	±3.0%	584	413	431	26	14	15
	±4.0%	475	358	415	14	10	10
8ϕ	±1.0%	992	775	1010	160	118	161
	±2.5%	419	305	324	27	18	17
	±3.0%	363	264	269	20	13	11
	±4.0%	355	249	261	15	8	8

The higher ductile cyclic performance of DPF respect to B450C is then evident: N_{cycles} was, normally, almost the 50% higher, especially for high imposed strain and L_0 equal to 8ϕ respect to B450C. Same results, with an increase of at least the 30%, were visible in terms of dissipated energy. An improvement of the ductile performance was also appreciable in case of DPD for L_0 equal to 8ϕ, where comparable results were achieved in terms of dissipated energy while more cycles were needed to reach the failure.

The small differences between DPF and DPD steels can be related to the different amount of martensite and ferrite.

3.2 *Performance in corroded conditions*

The mechanical performance of DPD, DPF and – for sake of comparison B450C TempCore® steel – were assessed also in corroded conditions. Accelerated salt-spray chamber tests were performed following the procedure described in Caprili et al. (2019). Two different exposure periods, respectively equal to 45 and 90 days in salt-spray chamber, were adopted.

The selected typology of accelerated corrosion test, with the advantage of being codified through a ASTM G109-07 (2007) standard, was used to represent mainly uniform corrosion conditions; consequently, the most relevant Corrosion Damage Indicator (CDI) used to determine the entity of aggressive attack on bars, was the *Mass Loss* (ML), evaluated with reference to the effective exposed length to corrosion (L_{corr}, being equal to about 90 mm).

For each steel grade and for each exposure period, on corroded specimens tensile and LCF tests – following the same protocols adopted for the reference condition – were performed; at least five samples for each testing condition were considered.

Average ML achieved were equal to 3.95%, 4.28% and 4.0% after 45 days and equal to 6.6%, 8% and 7.1% after 90 days respectively in case of DPF, DPD and B450C for specimens of length equal to 500 mm, used for tensile tests. In case of specimens of lower length – i.e. 250 mm used for the assessment of the LCF performance - average ML were almost the same in case of DPF and B450C, respectively equal to 4.0% and 6.5% after 45 and 90 days of exposure, being otherwise slightly lower in case of DPD, up to 3.5% and 6.0% for the two considered exposure periods Figure 5)..

As a general remark, these values indicate no relevant differences in terms of corrosion entity amongst DPF, DPD and B450C.

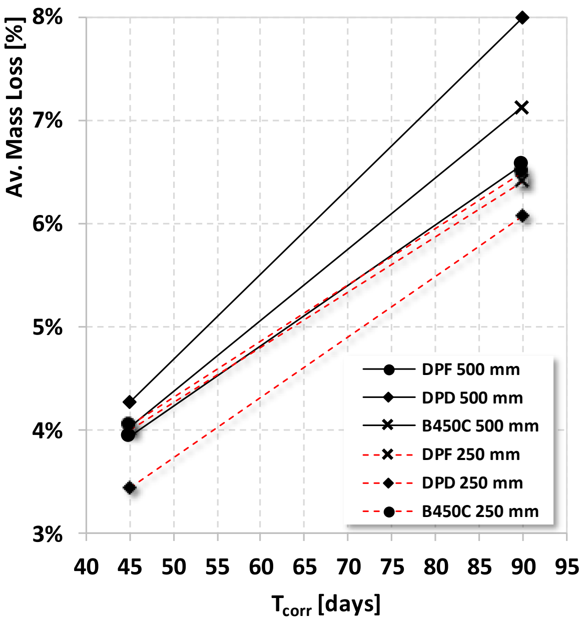
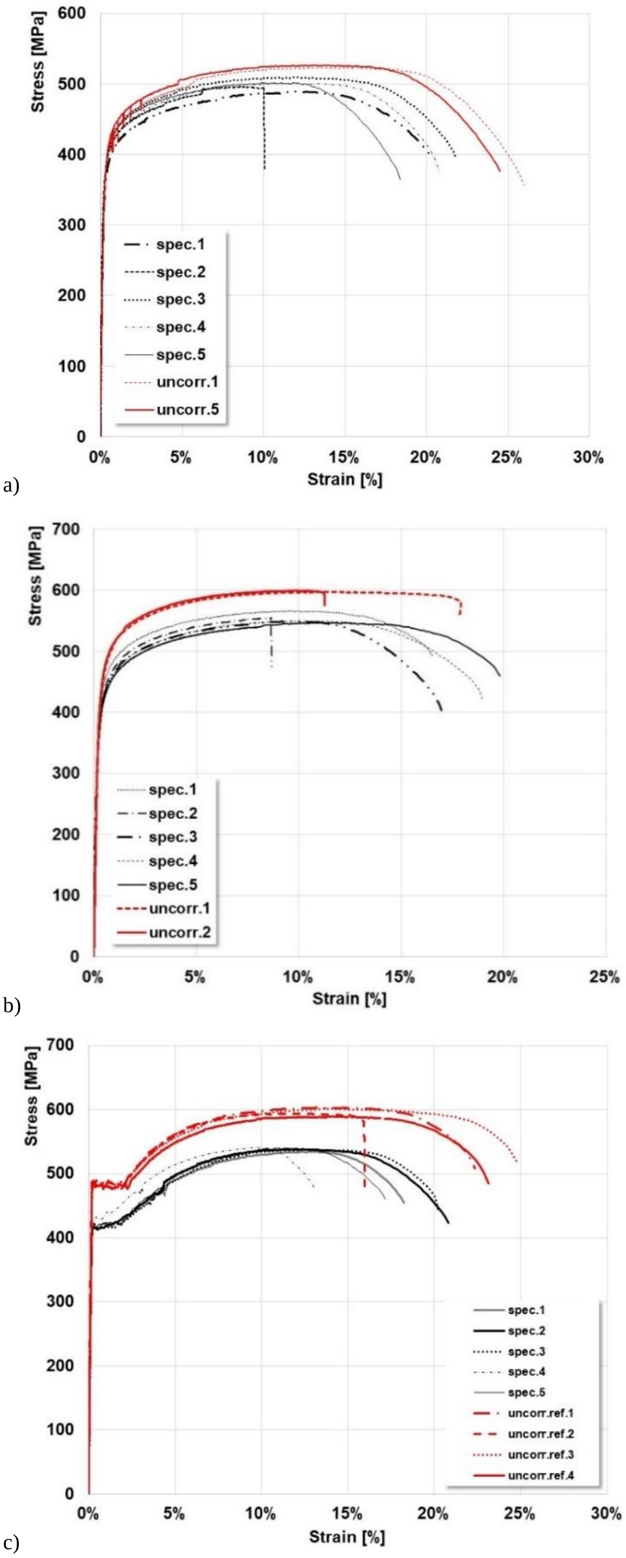


Figure 5. Variation of ML in relation to exposure period considering different length specimen (Caprili et al. 2019).

Results of monotonic tensile tests on corroded specimens are presented in terms of *average residual values* of the mechanical properties achieved from tests on five specimens (both for 45 and 90 days of exposure - Table 4, Figure 6). *Residual values* (Res) indicate the percentage ratio between corroded and reference measures of strength and deformation capacity; manual measures of strain are presented. Stress values refer to the effective cross section of the rebar before corrosion: this is conventional according to what already presented by Imperatore et al. (2017). Since corrosion generates the reduction of the cross section of the bar, the decrease of the load causing failure does not really correspond to lower strength when evaluated referring to the corroded cross section.

As visible from Table 4, corrosion had not relevant influence on the mechanical properties in terms of strength of reinforcing steels, especially in the case of DP grades – where the residual values of R_e and R_m were almost the 100% of the initial one. On the other hand, the improvement of DP steel concerning deformation capacity was evident: the residual values of A_{gt} for comparable values of mass loss were higher in case of DP grades respect to TempCore®.

For ML around 4% (exposure period 45 days) the average residual A_{gt} of DPF and DPD were respectively equal to 63.9% and 64.4% towards 48% of B450C (Figure 7), and the same was assessed for higher ML (corresponding to 90 days of exposure: about 50% of $ResA_{gt}$ for DP grades towards 36% of B450C).



a)

b)

c)

Figure 6. Stress-strain curves achieved from tensile tests on a) DPF, b) DPD and c) B450C corroded specimens with comparison to uncorroded/reference condition (in red).

Table 4. Average results of tensile tests on corroded specimens.

Steel Grade	T_{corr} (days)	ML (%)	$ResA_{gt}$ (%)	$ResA_5$ (%)	$ResR_e$ (%)	$ResR_m$ (%)
DPF	45	3.95	63.9	82.8	99.7	96.9
DPF	90	6.58	51.4	72.7	97.1	95.1
DPD	45	4.28	64.4	83.8	97.7	96.5
DPD	90	7.99	48.9	79 .0	90.9	93.3

B450C	45	4.03	48.0	89.5	94.2	93.3
B450C	90	7.13	36.0	79.2	86.2	89.4

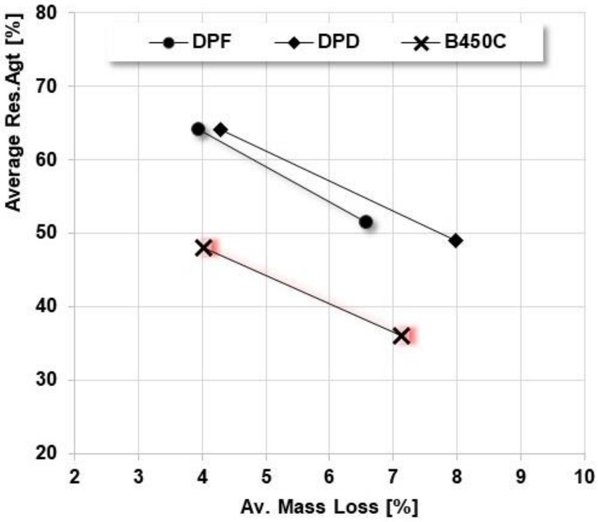


Figure 7. Average values of residual A_{gt} vs average ML.

Concerning the cyclic performance, DPF, even if characterized by lower values of strength, showed a higher cyclic performance in corroded conditions respect to B450C, in terms of both *dE* and N_{cycles}. No relevant differences were observed, otherwise, between DPD and TempCore® reinforcing steel.

This indicates that corrosion does not strictly influence the failure modality under LCF condition: corrosion generates alterations of the surface responsible for the premature initiation of fatigue cracks and of rebar’s failure, but the resulting LCF behaviour is less affected by ML (in the considered range) respect to the monotonic one (Figure 8).

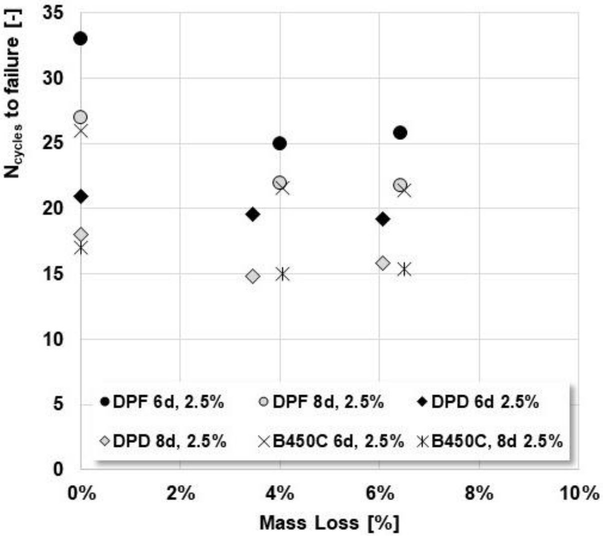


Figure 8. Number of cycles to failure (LCF) in corroded and uncorroded conditions for the different grades considered (Caprili et al. 2019).

4 CONCLUSIONS

The production process needed to achieve steel reinforcing bars with Dual-Phase (DP) microstructure was fully analysed to have the possibility to obtain reinforcements provided by strength and deformation capacity comparable to what already provided by TempCore® steels but – in parallel – characterized by enhanced durability towards corrosion. The improved corrosion performance are due to the mixed microstructure in which the martensite – main responsible for corrosion – is not directly exposed to the environmental attack inhibiting the initiation (and following propagation) of corrosion.

In the present paper, the results of the mechanical characterization of DP grades – namely DPF and DPD in relation to different chemical compositions and C-amount – are presented in comparison to the ‘ordinary’ TempCore® B450C steel grade. Rebars of diameter 16 mm were considered; tensile and cyclic (low-cycle fatigue) tests were performed in reference and corroded conditions. Corrosion was represented through accelerated tests in salt spray chamber.

In reference condition, Dual-Phase steel DPF showed good properties in terms of A_{gt} in both monotonic and cyclic conditions, with *dE* and N_{cycles} higher than B450C especially in the case of high buckling length and imposed strain; a slighter improvement was also provided in case of DPD.

Concerning the corroded condition DPF, DPD and B450C almost presented the same values of mass loss both in the case of 45 and 90 days in salt-spray chamber; for the same ML, the effects of corrosion highly differed since DP grades evidenced a lower reduction of A_{gt} respect to TempCore® (64% vs 50% for ML around 4% and 50% vs 36% for ML around 7%), due to their microstructure.

No specific effect of corrosion on the cyclic behaviour was, otherwise, appreciated. The small reduction of the dissipative capacity, evident from the results of LCF tests, could not be directly related to corrosion entity in terms of ML, being explained with modifications of the surface and the mechanisms of fatigue initiation.

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