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A new generation of high-ductile Dual-Phase steel reinforcing bars

Silvia Caprili [a],*, Walter Salvatore [a], Renzo Valentini [a], Cristiano Ascanio [b], Gianbruno Luvarà [b]

[a] Department of Civil and Industrial Engineering, University of Pisa, Largo L. Lazzarino 1, 56122 Pisa, Italy
[b] Ferriere Nord S.p.A., Zona Industriale Rivoli di Osoppo, 33010 Osoppo, Udine, Italy

HIGHLIGHTS

- Steel rebars shall provide adequate ductility for construction in seismic areas.
- Durability problems affect TempCore® reinforcements causing decrease of ductility.
- Dual-Phase steels have good mechanical and durability performance.
- Industrial reinforcing steel plants need to be adapted to DP steel production.
- Production costs shall be limited allowing DP bars commercialization.

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ABSTRACT

The development of a new typology of enhanced steel reinforcing bars is presented, including aspects related to the industrial production process, microstructural and mechanical characterization of achieved samples, is presented. Dual-Phase steels, provided by a ductile ferrite matrix in which a second hard martensite phase is embedded, are widely used in the automotive sector due to their excellent performance in terms of ductility and durability. For the same reasons, Dual-Phase steels can represent a valid alternative to current steel reinforcements – mainly TempCore® – that, as highlighted by the current scientific literature, are affected by relevant decrease of ductility in case of corrosion attack. The present paper shows the results of investigations executed to produce DP bars in reinforcing steel industrial plants; the experimental characterization is provided too.

1. Introduction

Reinforced Concrete (RC) buildings in seismic areas shall be designed following the *capacity design* approach (D.M.14/01/2008 [1], EN1998-1:2005 [2], FEMA356 [3]). High inelastic deformations are expected in dissipative regions to achieve the development of global collapse mechanisms without relevant losses of strength and stiffness of bearing elements. The dissipative capacity of the structure μ_d (i.e. ability to deform beyond the elastic limit without unexpected brittle failures) depends upon the element ductility μ_θ (i.e. rotation), the section ductility μ_χ (i.e. curvature) and the material ductility μ_ε (i.e. strain). This chain highlights how the ductile behaviour of reinforcements influences the performance of the whole building, and specific requirements for structural details and material properties are then imposed.

Minimum values of the mechanical parameters of reinforcing bars – yielding and tensile strength (R_e, R_m), elongation at maximum load (A_{gt}) and hardening ratio (R_m/R_e) – shall be respected: Annex C of Eurocode 2 [4] defines three ductility classes for bars (A, B, C) characterized by increasing levels of minimum A_{gt} and R_m/R_e; Eurocode 8 [2] limits the use of class B to buildings designed for Medium Ductility Class and imposes class C for High Ductility Class. Italian standards for Constructions [1] allows class A only for stirrups.

Up today, the most diffused typology of steel for rebars in European constructions is TempCore®. The TempCore® process is characterized by two following phases of quenching and self-tempering and provides good strength and ductility towards moderate production costs, especially if compared to Micro-Alloyed steels. The addition of alloy elements (i.e. Vanadium, Niobium, etc.) increases the economic impact consequently restricting their employment. Recent scientific works (Apostolopoulos [5]; Apostolopoulos and Papadakis [6]; Al Hashemi et al. [7]; Caprili and Salvatore [8]; Meda et al. [9]; Imperatore et al. [10]; Zhang et al. [11]) otherwise highlighted TempCore® durability problems and drops of ductility and dissipative capacity if exposed to aggressive conditions, both in the case of localized and uniform corrosion.

The estimation of the expected residual mechanical properties after a specific corrosion exposure is possible basing on experimen-

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* Corresponding author.
E-mail address: silvia.caprili@ing.unipi.it (S. Caprili).

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tal data (Caprili et al. [12]; Cairns et al. [13]). Corrosion reflects in reduced structural performances due to materials' degradation (Caprili and Salvatore [8]; Caprili et al. [14]; Berto et al. [15]; Saetta et al. [16]; Braga et al. [17]; Kashani et al. [18]), reduction of rebars' cross section, cracking and spalling of concrete cover with modification of bond strength (Salvatore et al. [19]; Di Carlo et al. [20]). The degradation of mechanical properties is widely described both in case of monotonic and cyclic loads [9,10]. Kashani et al. [21,22] evidenced a 40% decrease of the dissipated energy due to corrosion attack and the strong influence of the inelastic buckling length. RC elements artificially subjected to corrosion phenomena showed the reduction of the bearing capacity respect to the undamaged condition [9]. Several numerical models for both concrete and reinforcing steel allow to represent the structural performance of corroded samples and to estimate the residual capacity in relation to exposure [17–20].

Two main routes can be pursued to solve or minimize corrosion effects: a '*direct*' and an '*indirect*' method. The indirect method consists in the adoption of higher concrete classes, thicker concrete covers, higher diameter rebars, etc. [8–19]. By this way, corrosion effects are minimized, but the source still exists: this is the method proposed by European standards [4–23]. The other possibility is to avoid corrosion initiation and propagation by selecting opportune materials *less* exposed to durability problems.

During the last years the scientific interest in the possibility to adopt enhanced steels for rebars strongly increased. Maffei et al. [24] and Salvatore et al. [25] analysed the possibility to adopt, for civil constructions, Dual-Phase (DP) steels. DP steels are widely used in the automotive sector since characterized by excellent ductile properties and improved durability performance due to their specific micro-structure, characterized by a ferrite matrix in which martensite is directly embedded.

Preliminary investigations concerning RC-DP structures [25] highlighted the improved performance of sections in terms of M-χ relationship, with curvatures higher and more distributed respect to RC-TEMP ones. The higher ductility of DP steels can lead to greater ductility of RC elements: DP steel enables attaining better performance in the post-elastic field thanks to the enlargement of the plastic zone within the element. Results of mechanical investigations on DP rebars [24] highlighted average values of the hardening ratio (R_m/R_e) around 2.0 and high elongation. The upper limitation of R_m/R_e to 1.35 prescribed by Eurocodes for reinforcing steels [2] limits, consequently, the application of DP steels to civil constructions, requiring the update of current standard codes.

The use of DP steel in constructions is, currently, limited by industrial aspects: the achievement of DP bars need the improvement/modification of steel reinforcing plants and of the production process. Costs shall be, otherwise, limited to allow the commercialization of the product compared to ordinary reinforcing steels.

The present paper shows the procedure elaborated to produce DP rebars using actual plants, including selection of chemical composition, analysis of the thermal process, investigation of the production aspects and microstructural and mechanical investigations. A multilevel procedure is proposed and presented together with the results of the mechanical characterization under monotonic and cyclic actions of produced DP rebars. The work has been developed within the European research project NEWREBAR *"New Dual-Phase steel reinforcing bars for enhancing capacity and durability of anti-seismic moment resisting frames"* (2015–2019), funded by the Research Fund for Coal and Steel (RFCS) of European Commission.

2. Dual-Phase steel characteristics

Dual-Phase steels are characterized by a composite microstructure made up of a ductile ferrite matrix in which a second hard martensite phase is embedded, in a proportion of about 20% by volume. The lack of a well-defined interface make dislocations free to move in the ferrite phase, being blocked on the martensite islands.

The martensite phase provides the strengthening effect while the soft matrix ensures high formability; other phases (bainite, perlite and residual austenite) may also be present in small quantities. Properties such as continuous yielding behaviour, uniform plastic deformation and high elongation, excellent strength and formability combinations were responsible of the wide application of DP steels in the automotive sector Movahed et al. [26].

DP microstructure is currently achieved through two different processes: *as-rolled* or by *intercritical annealing* in alpha-gamma α-γ field after cold-rolling. Intercritical heat treatment is the simplest way to transform low alloys steels (Carbon content $\leq$0.2%) into DP microstructure with enhanced strength/ductility combination [26]. The process foresees quenching in the intercritical temperature range ($A_1 \div A_3$), where the austenite phase transforms to martensite, giving rise to a ferrite/martensite microstructure instead of the conventional ferrite/pearlite one.

The applied thermal treatment consists of a first heating stage within the intercritical region of austenite (where nucleation occurs in the ferrite matrix), with carbon content higher than the nominal one, and by a rapid cooling stage, promoting the transformation of the austenite into martensite (Salvatore et al. [25]; Dossett and Totten [27]; Caprili et al. [14]). The Intercritical Quenching (IQ) process creates a harder phase in the ferrite matrix, with high residual stresses and the increase in the density of the mobile dislocations in correspondence to the ferrite/martensite interface.

The mechanical behaviour of DP steel stems precisely from the formation of a two-phases ferrite/martensite structure. DP Properties depend on the morphological characteristics of the two phases, related to the annealing temperature and time, to the annealing procedure, to the presence of alloying elements, and, besides, to the quenching media and rate. Properties can consequently strongly vary as a function of the desired objective and of the foreseen application (Thomas [28]; Bayram et al. [29]).

In the worldwide scenario, just few grades of DP steel are produced directly from hot rolling process (e.g. DP800). Through cold rolling and IQ process is it possible to achieve higher DP grades (e.g. DP1000) with improved ductility/durability performance by 'adapting' the current production process without significantly changing the industrial plants, keeping the costs relatively low.

The scientific interest in DP steels is well-known. Zhang et al. [11] – through tensile tests on specimens subjected to IQ at 780 °C – showed the improvement of strength, weldability and corrosion resistance of DP steels respect to the 'as received' material (hot-rolled weathering steel plates with ferrite/pearlite structure). The achieved mechanical properties were, as expected, function of the IQ temperature: the increase from 760 °C to 820 °C highlighted the 3% of decrease of the total elongation and, on the contrary, the increase of yielding strength. Data concerning corrosion effects were also provided: the corrosion rates (mm/a) in the case of DP steels were significantly lower than the ones in the 'as delivered' condition.

Sarkar et al. [30] executed corrosion tests on DP steels through IQ treatments with temperatures in the range 735 °C ÷ 775 °C. Galvanostatic polarisation technique was used to study the durability properties of the heat-treated specimens in 3.5% NaCl solution. Corrosion results depended upon the volume fraction and morphology of the phase constituents: higher amount of martensite decreased the durability of DP steels, while "island martensite morphology" provided better corrosion resistance properties. Trejo et al. [31] observed that better corrosion resistance of DP steels respect to standard billet reinforcement in concrete. Similar conclusions were derived from the experimental campaign performed by Keleştemur and Yıldız [32], highlighting corrosion rates of DP steel proportionally increasing with martensite amounts.