Abstract

The load bearing capacity of reinforced concrete structures after fire can be assessed if the modified mechanical properties of the building materials, designated here as ‘residual’, are known. In this respect, the residual properties of reinforcing steels produced (a) by the Tempcore process; (b) microalloying with vanadium; and (c) work-hardening, all falling into grade FeB500S, were selected for investigation, aiming to represent a wide range of steels currently available for the construction industry in Europe. For both the microalloyed with vanadium and for the work-hardened reinforcing steels typical diameters were investigated. For the Tempcore-type reinforcing steels, due to their heterogeneous structure, the effect of size and composition have been also examined. Specimens of the above types of steel were heated at temperatures ranging from 200 °C to 800 °C for 1 h and then cooled in air to room temperature. Thereafter, their residual properties were assessed by hardness measurements, tensile and Charpy-V impact tests. Metallographic analysis was used to correlate mechanical properties to microstructural characteristics.

From the above investigation it was concluded that the Tempcore steels presented the more stable behavior up to temperatures of 500 °C, while the microalloyed steel, although it presented very satisfactory tensile properties, displayed low impact toughness due to coarsening of vanadium carbides. The work-hardened steel showed a continuous drop of its properties from approximately 250 °C and suffered from brittleness in the vicinity of 200 °C due to strain aging phenomena.

Keywords: Reinforcing steel; Microstructure; Mechanical properties; Fire

1. Introduction

Actual methods for the production of high-strength concrete reinforcing steels may be classified into three distinct categories:

The first one consists of steel bars slowly cooled in air after hot rolling (hot rolled steels). For these steels, modifying their chemical composition can increase the yield strength, however, for sake of weldability the carbon and manganese levels should be kept low and this necessarily results in low strength. As an alternative issue, small additions of strong carbide formers, such as Nb and/or V, may enhance the yield strength without affecting weldability [1–3]. This solution leads to ‘the hot rolled microalloyed with vanadium or niobium steels’, but it is rather expensive, so that use and production of these steels is not widespread.

The second category consists of bars submitted to specific thermomechanical strengthening processes, bearing trade-names such as Tempcore, Thermex, etc. The designation ‘Tempcore’ was adopted since it reflects the principle on which it is based, i.e. tempering of a previously quenched surface layer, under the effect of heat supplied by the core of the bar [4–6].

‘Work-hardened steel’ bars, which acquire their service properties by slight cold deformation through twisting, drawing or rolling, fall within the third production category. For such bars, increasing the amount of strain results in increasing the yield strength. Moreover, it greatly reduces their ductility.

Reinforced concrete structures may suffer from high service temperatures in the case of fire. The load bearing capacity of structures after fire can be assessed only if
the modified mechanical properties of the building materials are known. These modified properties, that the steel exhibits after it has been submitted to a complete cycle of heating and cooling, will be designated as ‘residual’.

The effect of elevated temperatures upon the residual mechanical properties of hot rolled and work-hardened reinforcing steels has been reported in previous investigations [7,8]. As it has been shown, the manufacturing process for the reinforcing steel does have an effect on the residual yield and tensile strength, with the ‘cold worked’ steels presenting a greatly reduced strength with increasing heating temperature compared with the ‘hot rolled’ steels. The influence of heating on microstructure and properties of thermomechanically strengthened reinforcing steels of strength class AIV and AV (yield and ultimate strength greater than 900 MPa and 1100 MPa, respectively) has drawn extensive research work [9–13]. Nevertheless in Europe, grades of much lower strength such as the 400 and 500 MPa grade or, in some countries, 600 MPa are common grades. Although the Tempcore process is the main production type of high-yield reinforcing steels after 1985 in Europe and Australia, there is an absence of experimental data concerning their endurance to fire. Despite the interest shown towards microalloying of steel and the corresponding enhancement of properties [1–3], experimental data concerning the endurance of microalloyed reinforcing steels to fire has not received the same extent of research as for example in the case of hot rolled or work-hardened steels.

Unfortunately, much of the previously reported research work on reinforcing steels of different strength classes does not easily lend itself to quantitative evaluation, as to correlate residual mechanical properties to the manufacturing processes. In this comparative study, the effect of heating on microstructure and mechanical properties of all categories of reinforcing steels of the 500 MPa (yield strength) class produced (a) by the Tempcore process; (b) by hot rolling after microalloying with vanadium; and (c) by work hardening of hot rolled steels were investigated. The changes of mechanical properties after heating to a temperature range between 200 and 800 °C were assessed by hardness measurements, tensile tests and Charpy-V impact tests. Metallographic analysis, using both optical and electron microscopy, was used to correlate mechanical properties to microstructural characteristics and to determine, where possible, the impact of the manufacturing process on the residual mechanical properties after heating.

2. Experimental procedure

Reinforcing steels produced (a) by the Tempcore process; (b) microalloying with vanadium; and (c) work-hardening, all falling into grade FeB500S [14], were selected to represent a wide range of steels currently available for the construction industry in Europe. Size, mechanical properties and composition of reinforcing steels investigated are given in Tables 1 and 2. For each type and diameter of steel bars, specimens coming from the same ingot were taken.

In order to estimate the effect of bar size of the Tempcore-type reinforcing steels, two sets of specimens, namely of 8 and 12 mm diameter bars, were investigated. Furthermore, in the case of 8 mm diameter reinforcing bars, specimens from two different ingots were taken, aiming to assess the effect of different chemical composition.

For the hot-rolled microalloyed with vanadium reinforcing steel, specimens from 12 mm diameter bars were examined.

Finally, in the case of work-hardened reinforcing steels, specimens from 8 mm diameter bars were investigated, because this diameter is the most commonly used in this category of steels.

Specimens of all the above types of steel were heated in an electric furnace for 1 h and then cooled in air to room temperature. The furnace temperature was initially raised and when the desired level was attained, specimens were put into the heating chamber. To simulate

<table>
<thead>
<tr>
<th>Element</th>
<th>Microalloyed</th>
<th>Tempcore A</th>
<th>Tempcore B</th>
<th>Tempcore C</th>
<th>Work hardened</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.250</td>
<td>0.236</td>
<td>0.238</td>
<td>0.160</td>
<td>0.228</td>
</tr>
<tr>
<td>Mn</td>
<td>1.220</td>
<td>0.910</td>
<td>1.409</td>
<td>0.770</td>
<td>1.387</td>
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<td>Si</td>
<td>0.298</td>
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<td>0.211</td>
<td>0.195</td>
<td>0.198</td>
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<tr>
<td>S</td>
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<td>0.032</td>
<td>0.035</td>
<td>0.019</td>
<td>0.030</td>
</tr>
<tr>
<td>P</td>
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<td>0.036</td>
<td>0.031</td>
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<td>0.023</td>
</tr>
<tr>
<td>N</td>
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<td>0.014</td>
<td>0.020</td>
<td>0.016</td>
<td>0.016</td>
</tr>
<tr>
<td>Cu</td>
<td>0.519</td>
<td>0.359</td>
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<td>Cr</td>
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<td>0.112</td>
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<tr>
<td>Mo</td>
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<td>0.025</td>
<td>0.037</td>
<td>0.030</td>
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</tr>
<tr>
<td>Ni</td>
<td>0.107</td>
<td>0.128</td>
<td>0.096</td>
<td>0.145</td>
<td>0.103</td>
</tr>
<tr>
<td>V</td>
<td>0.075</td>
<td>0.030</td>
<td>0.002</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Ceq</td>
<td>0.536</td>
<td>0.444</td>
<td>0.536</td>
<td>0.358</td>
<td>0.519</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Yield strength (MPa)</th>
<th>Ultimate strength (MPa)</th>
<th>Strain (%)</th>
<th>Toughness (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microalloyed</td>
<td>12</td>
<td>531</td>
<td>740</td>
<td>19</td>
</tr>
<tr>
<td>Tempcore-A</td>
<td>8</td>
<td>570</td>
<td>655</td>
<td>24</td>
</tr>
<tr>
<td>Tempcore-B</td>
<td>8</td>
<td>616</td>
<td>716</td>
<td>14</td>
</tr>
<tr>
<td>Tempcore-C</td>
<td>12</td>
<td>597</td>
<td>692</td>
<td>15</td>
</tr>
<tr>
<td>Work-hardened</td>
<td>8</td>
<td>640</td>
<td>691</td>
<td>14</td>
</tr>
</tbody>
</table>

ND = Not determined.

1 Residual strain after rupture.

2 Charpy-V notched impact toughness.
temperatures likely to be experienced by the steel during a fire, a temperature range from 200 to 800 °C was adopted. The 200 °C temperature was in most cases the lowest temperature tested, since the properties of the steel are not significantly altered below this limit. Nevertheless, in the case of the microalloyed steel, a heating temperature of 100 °C was also included in the experiments, so that possible embrittlement behavior, due to aging, could be examined. The upper limit of 800 °C was used because, in a fire, the steel bars of the construction elements are not usually subjected to temperatures higher than this.

After the reinforcing steel bars were submitted to a complete cycle of heating and cooling, specimens for microscopical characterization, tensile tests and Charpy-V toughness evaluation were cut out.

Specimens for optical and SEM microscopy were prepared using standard laboratory techniques of grinding and polishing. Microalloyed reinforcing steels were investigated using additionally transmission electron microscopy (TEM). Specimens were prepared by jet electropolishing, but since selective thinning of ferrite occurred while the carbides remained in a state unsatisfactory for observation, this stage was followed by a further stage of ion beam thinning. During ion beam thinning material is removed with comparable rates for obtaining samples with electron transparent areas within carbides and carbide/ferrite interfaces.

Tensile tests were carried out on samples according to ISO 6892 [15]. The tensile machine used was an Instron model 5594-HVL of 100 tons capacity. For each size and type of reinforcing steel and after each heat treatment two tensile tests were carried out. The values were recorded using the machine’s own plotter and a computer connected to a data logger. The residual tensile yield and ultimate strength and the residual strain after rupture were measured for the as-received materials and for the samples after a complete cycle of heating and cooling.

Toughness of reinforcing steels was evaluated using the Charpy-V-notched test method. The length of the specimens was 60 mm. Due to lack of recommendations for testing concrete reinforcing steel rods [4] a number of preliminary tests were carried out to determine the suitable notch depth. The fracture energy provided from the Charpy-V pendulum is limited to 300 J, so a notch depth of 4 mm and 5 mm for the 8 mm and 12 mm bar diameters, respectively, was necessary in order to ensure fracture of the test specimens. The notch flank angle was 60° and the notch radius 0.5 mm. The notch preparation of Charpy-V specimens was carried out after the heat treatment of the reinforcing steel bars. For each size and type of reinforcing steels, three Charpy-V samples were prepared. Normalized values of the absorbed energy to fracture, i.e. the ratio of the residual value to the initial value of the as received material were used for comparison between different manufacturing processes.

3. Results

3.1. Metallography

The Tempcore process leads to reinforcing bars that exhibit a composite microstructure. In a typical cross-section of the bars, three main zones are observed, shown on the macrograph of Fig. 1a: (1) a ferrite–pearlite core; (2) an intermediate layer with a mixture of bainite and ferrite; and (3) a tempered martensite layer on the surface. The above layers are shown in the micrographs of Fig. 1b, c and d, respectively.

Microstructural changes during heating of the steel bar are mainly localized in the outer layer of the cross section, where tempering phenomena of martensite are pronounced, Fig. 2. This is corroborated by microhardness measurements, showing that extensive softening of the outer hard layer occurs at 600 °C for the 8 mm diameter Tempcore bar (Fig. 3a) and at 700 °C for the 12 mm diameter bar (Fig. 3b). The difference should be presumably attributed to their different chemical composition. Nevertheless, the outer layer always remains harder than the core, even at temperatures as high as 700 °C, due to its fine microstructure of tempered martensite.

The microalloyed steel consists of a ferritic matrix with relatively small colonies of troostite, Fig. 4a. The grain size of the material is fine and should be attributed to vanadium, having a relatively small solubility in austenite [16,17] and leading to refinement of austenitic grains during hot rolling. Fig. 5a is a TEM micrograph, showing a relatively high density of dislocations and their pinning on fine precipitates dispersed in the ferritic matrix. During isothermal transformation of austenite there is a strong tendency for vanadium to partition away from the growing ferrite and to form vanadium carbides and/or nitrides. These precipitates serve as effective barriers to the motion of dislocations within the ferritic grains, increasing the yield strength.

Heating the microalloyed steel results in coarsening of the existing precipitates and at the same time new precipitation of vanadium carbides takes place along the ferrite grain boundaries. This intergranular precipitation becomes evident from the well-marked boundaries around the ferrite grains, shown in optical micrographs of Fig. 4b,c. These precipitation phenomena occur at temperatures up to approximately 500 °C and are accompanied initially by a slight increase of microhardness up to 300 °C, which thereafter becomes constant up to 500 °C, Fig. 6. During this stage, transmission electron microscopy (TEM) reveals cell formation within the ferrite grains and coarsening of the VC particles along the ferrite grain boundaries, as shown in Fig. 5b.
Fig. 1. (a) Typical cross-section of a Tempcore bar and optical micrographs of the (b) core, (c) intermediate layer and (d) outer hardened and self-tempered layer.

The microstructure of the work-hardened reinforcing steel bars consists of a mixture of ferrite and pearlite, Fig. 7a. Metallographic cross-sections parallel to the axis of the bar, which have been analyzed by quantitative metallography, indicate a 2% strain hardening. As a matter of fact, the high strength in this type of steel bars is achieved by cold drawing.

No significant microstructural changes occur after heating of the steel up to 300 °C, however, a slight increase of hardness in this temperature range indicates that strain aging phenomena have occurred, Fig. 6. Heating further up to 600 °C causes only recovery phenomena, as it is certified by a constant drop of hardness without remarkable microstructural changes, Fig. 7b,c. As a matter of fact, the degree of work hardening (approx. 2%) is not sufficient to cause recrystallization. Heating over 700 °C is associated to partial annealing, accompanied with a small increase in hardness, due to refinement of the microstructure.

3.2. Tensile testing

The residual mechanical properties of the different types of steel bars as a function of the heating temperature are presented in Fig. 8a–d. On the same graphs, a dashed line indicates the corresponding minimum allowed values according to actual standards.

3.2.1. Effect of heating on the yield strength (Re)

The residual yield strength is of prime importance for the security of the buildings after fire. As a matter of
fact, the conventional design of concrete reinforced structures is based on the assumption that loads, which normally appear in service, induce only elastic stresses on the reinforcing steel. In this case, the safety of a structure can be defined in terms of the ratio between the service stress and the yield stress of the reinforcing bars.

One should note that steel type and chemical composition affects strongly the initial yield strength. For the steels investigated here, the initial yield strength varies in a wide range between 550 and 640 MPa, although the steels belong all to the 500 MPa class. By comparing the investigated Tempcore A and B bars, it is seen that Tempcore B is much stronger than Tempcore A, presumably due to its higher manganese content, see Tables 1 and 2.

The evolution of the residual yield strength with temperature shows also significant differences for reinforcing steels produced by different manufacturing processes as well as for different sizes and compositions in the case of the Tempcore-type bars, Fig. 8a.

The 12 mm Tempcore-C bar begins to soften from 200 °C, showing an earlier decrease of its yield strength compared to both Tempcore-A and -B bars with 8 mm diameter. The latter do not show any considerable change of their yield strength up to approximately 500 °C. Composition is, however, not found to have a remarkable effect on the critical temperature above which the residual yield strength becomes lower than the standard allowed value of 500 MPa. This temperature lies for all Tempcore steels examined here between 550 and 600 °C.

The yield strength of the hot rolled microalloyed steel, after an initial increase up to 100 °C, stabilizes in the temperature interval of 100–400 °C and then drops continuously. The critical temperature above which the yield strength becomes lower than the standard allowed value of 500 MPa is approximately 550 °C.

In the case of the work-hardened steel, a slight increase of the yield strength up to 200 °C, along with a significant decrease of the residual strain after fracture (Fig. 8c) is attributed to strain aging. Then the yield strength drops continuously up to the temperature of 600 °C, where it stabilizes at only 60% of its initial value. The critical temperature under which the yield strength becomes lower than the allowed value of 500 MPa is in this case 500 °C.

3.2.2. Effect of heating on the ultimate tensile strength (Rm)

With regard to the evolution of the residual tensile strength, heating has an effect very similar to that examined for the yield strength, for all types of steels examined here. From Fig. 8b, it is observed that the ultimate strength remains high up to 400 °C for all types of steels, afterwards it begins to drop down. It should be noted that the decrease of the tensile strength of the microalloyed steel is very strong after 400 °C compared to that of the Tempcore and cold worked steels. However, due to its higher initial tensile strength the microalloyed steel shows a superior absolute value than the other two types of reinforcing steels for temperatures as high as 700 °C. As far as the minimum standard allowed value of 550 MPa is concerned, heating is not critical, as all steels, with the exception of Tempcore B, retain acceptable values of ultimate strength up to 700 °C and even higher.

3.2.3. Effect of heating on the ductility

Research work by the European Committee for Concrete (C.E.B.) has led to the conclusion that the conven-
tional elastic stress based calculation is not sufficient, since for several structures local plastic deformations may be absorbed without failure of the reinforcing steel [6]. Under these circumstances, the safety of a building could be expressed in terms of a strain ratio between the local plastic deformation liable to occur and the uniform elongation of the reinforcing bar. This consideration greatly relies on the ductility of the steel. There are many ways, direct or indirect, to assess ductility, the most usual being the residual strain after rupture.

The evolution of the residual strain after rupture as a function of temperature for all steels examined is shown in Fig. 8c. For the microalloyed steel, it is stable up to 500 °C and then increases significantly. Tempcore reinforcing steels show approximately the same behavior as microalloyed steels but the residual strain is constant or slightly increasing up to 600 °C.

Cold worked reinforcing steel presents a pronounced reduction of strain after rupture when heating to 200 °C, which results to a significant loss of 40% of its initial value and falls under the standard allowed value of 12%. Afterwards the residual strain increases again. This is the only type of reinforcing steel that presents residual ductility problems after heating.

Another relevant expression of ductility involves a stress ratio between the ultimate tensile strength and the yield stress of the reinforcing bar (Rm/Re). The Rm/Re ratio deduced from the stress–strain diagram could be used as an indirect means to express the extent of uniform elongation before fracture, i.e. the elongation up to the ultimate tensile strength.

The influence of heating on the ratio between the residual ultimate strength and the residual yield strength is presented in Fig. 8d. As with residual strain after rupture examined above, the ratio (Rm/Re) is in general improved with heating or it remains practically unchanged over a wide temperature range. In all cases it is higher than the minimum allowed value of 1.08. It
Fig. 5. Transmission electron micrographs of hot rolled microalloyed with vanadium reinforcing steel bar (a) in the initial state and (b) after heating to 500 °C for 1 h.

should, however, be noted that it does not reflect the low ductility observed at 200 °C for the work-hardened reinforced steel.

3.2.4. Comparative strength–ductility (Neves) diagrams

The global influence of heating upon strength and ductility for each type of steel investigated here is presented in Fig. 9, according to the representation proposed by Neves et al. [8]. The graphs of Fig. 9 combine on one axis the residual ultimate strength and on the other axis the residual strain after rupture, both in normalized form, i.e. as a ratio of the residual to the initial value. The centerline in these graphs constitutes the boundary between two zones: (1) the left zone, where the increase in the residual tensile strength predominates with respect to the variation of the residual strain after rupture (brittle zone); and (2) the right zone, where the increase in residual strain after rupture predominates with respect to the variation of residual tensile strength (ductile zone).

From these diagrams, it comes out that only the work-hardened reinforcing steel is characterized by a temporary decrease of ductility at 200 °C, which has been attributed previously to aging. These results agree with that of Fig. 8c.

3.3. Charpy-V tests

The residual toughness of all types of reinforcing steels has been assessed using the Charpy-V test and the results are presented in Fig. 10, showing the normalized absorbed energy for fracture as a function of the temperature.

From this diagram, it comes out that both the Tempcore and the work-hardened steels maintain and even improve their initial level of toughness after heating to temperatures up to 700 °C. On the contrary, the microalloyed steel shows for the same temperature range an unexpectedly bad behavior, where the toughness drops to approximately 60–70% of its original value.

The high values of toughness measured in the case of the Tempcore steels should be attributed to the toughness of the fine tempered martensitic layer along with the ductile ferritic core. In the case of the work-hardened steels, the high levels of toughness should be attributed to the favorable orientation of grains (texture) caused by the deformation. As a matter of fact, the elongation of grains parallel to the axis of the bar serves as a barrier to the propagation of the crack, which takes place in a perpendicular direction during the Charpy test [18].

The microalloyed steel presents a strong decrease of toughness when heated in the temperature range between 200 and 600 °C. This decrease is clearly associated to
the precipitation phenomena described previously in Section 3.1. The presence of precipitates inside the ferrite does not allow significant plastic deformation during dynamic loading. Additionally, the precipitation of brittle particles along the grain boundaries is very similar in nature with the temper embrittlement of low alloy steels [19]. Precipitation of carbides along the grain boundaries of ferrite is a strong embrittling process [20], which cannot be counterbalanced by the beneficial phenomena of recovery, which were observed in the same temperature interval.

4. Discussion

The main production of reinforcing steels in Europe concerns the Tempcore steels. Work-hardened steels are less produced and microalloyed steels are restricted by their comparatively higher cost. Nevertheless, in some cases there is a tendency to replace the Tempcore with work-hardened or microalloyed steel bars especially as transverse stirrup reinforcements in prefabricated steel columns. This choice is justified by two reasons: (i) work-hardened and microalloyed steels have a better formability than Tempcore steels which are difficult to bend due to their external hard layer; and (ii) work-hardened steel coils are easier to handle.

In the case of fire, the static and dynamic properties of steel used as reinforcement may be seriously modified depending to a great extent on the type of steel used. Crucial parameters are the maximum attained temperature, the time spent at this temperature and the position of the reinforcement in a structure. Temperatures of 400 °C or more are likely to appear in the case of fire, while transverse reinforcements are usually exposed to the highest temperatures, because they are nearest to the surface of the building elements.

In this study all usual types of class 500 MPa steels were investigated after being subjected to heating over a wide range of temperatures, going from 100 to 800 °C for 1 h. This time is sufficient for most metallurgical phenomena to be accomplished.

From the tensile test measurements, it comes out that the critical temperature above which heating for 1 h causes the residual yield strength to fall below 500 MPa
is 550–600 °C, 600 °C and 500 °C for the Tempcore, microalloyed and strain hardened steel, respectively. Within this temperature range both the residual tensile strength and the residual strain after rupture preserve acceptable values for the Tempcore and for the microalloyed steels, while the work-hardened steel presents low ductility in the vicinity of 200 °C, due to strain aging.

In many respects the microalloyed with vanadium steel shows a more stable behavior during heating than the other types of steel. As a matter of fact, it shows a gradual increase of its residual yield strength of approximately 10% and a constant tensile strength as the temperature increases up to 400 °C, while its residual strain after rupture remains close to the initial value for temperatures up to 500 °C.

However, the behavior of steel in dynamic loading, as measured by the Charpy test, attains values as low as 60–70% of its initial value in the temperature interval 200–600 °C.

The effects of V and N additions on the yield strength of low carbon steels have been explored by means of regression models [2]. So far the improvement in the mechanical properties that are achieved with modest additions of vanadium has been attributed mainly to the precipitation of VC and V(C, N) within the proeutectoid ferrite that constitutes the major microstructural constituent of these steels and the grain refinement [16,17].

The most common expression relating the subgrain size to strength is a form of the Hall–Petch equation [20,21].

The examined microalloyed steel presents an increase of its yield strength, which is maintained constant approximately up to 400 °C. The maximum decrease of the yield strength is observed at 600 °C falling to a level of approximately 80% of its initial value. This
finding suggests that the contribution of dislocation strengthening is small because both residual yield and ultimate strength of the steel are not much affected after heating at 500 °C, up to which dislocation density decreases significantly. On the contrary, coarsening of the vanadium particles to the ferritic grain interface lead to a significant decrease of tensile and impact strength.

The fact that both yield and ultimate tensile strength are approximately stable up to 500 °C should be attributed to the Tempcore manufacturing process. For a given diameter and chemical composition of the steel, the properties of the steel can be varied to a large extent by choosing the duration of the fast cooling step. Cooling is applied to the bar as near as possible to the exit of the last finishing stand, resulting to a quenched skin. Subsequently, the core heats the quenched layer by conduction, leading to tempering of the hardened layer while the austenitic core transforms quasi isothermally. The temperature of tempering of the outer layer is very important for its stability after heating and varies between 550 and 650 °C, depending on the diameter of the bars. Microhardness measurements show an earlier decrease in hardness of the tempered outer layer for the smaller diameter Tempcore bars, Fig. 3. This indicates that the hardened outer layer of the smaller bar is tempered to a lower temperature compared to the larger diameter bar. Due to the low tempering of the outer layer by the relatively small heat capacity of the core, small diameter bars suffer in general from lower ductility than larger Tempcore bars and, therefore the Tempcore process leads to the optimum results in the case of large
diameter bars [5]. This is observed in the 8 mm Tempcore-B bar compared to the 12 mm bar diameter in the as received state. In order to compensate for this drawback, alloying of the steel can be an effective way in producing Tempcore bars of equivalent strength level. In this context, the increased initial ductility of the 8 mm diameter Tempcore-A is due to its chemical composition and more precisely to the V content (see Table 1). The addition of V, which is approximately half than that of the microalloyed steel, examined here, along with the Tempcore process, provides a material that exhibits nearly constant tensile properties after heating up to 500 °C.

Another point deserving consideration is the more pronounced decrease on tensile properties of the 12 mm diameter Tempcore-C bar compared to the 8 mm diameter A and B bars. Although the outer hardened layer provides extra strength to the bar, the overall tensile performance depends also on the core. The percentage of manganese and vanadium of the 12 mm diameter Tempcore C bar is 0.770% and 0.001%, respectively. Allooying the steel with manganese (1.220% and 1.409% for the Tempcore A and B, respectively) and with vanadium (0.03% and 0.02% for the Tempcore A and B, respectively) contributes to the higher strength of the core, as deduced from the microhardness measurements, Fig. 3. As already mentioned microhardness measurements show an earlier decrease of hardness of the tempered outer layer for the smaller diameter, Fig. 3, but the material of the inner core present higher microhardness compared to that of the 12 mm diameter Tempcore (C) bar. This explains why the 12 mm diameter Tempcore C bar presents inferior tensile values compared to the 8 mm diameter (A and B) bars in the initial state but also after heating over a wide range of temperatures (100–500 °C).

5. Conclusions

- The residual strength of a concrete structure depends not only on the strength grade of the reinforcing steel, but also on the steel manufacturing process.
- Heating of the microalloyed steel results in coarsening of the existing precipitates especially along the ferrite grain boundaries. This leads to a slight increase of yield strength between 100 and 400 °C, but to a significant decrease of impact toughness between 200 and 600 °C.
- Work-hardened steel bars show a continuous drop of the yield and ultimate strength starting at 200° and 300 °C, respectively, along with a continuous increase of impact toughness. A slight increase of hardness and a pronounced reduction of ductility to levels as low as 40% of its initial value, after heating to 200 °C, highlight the susceptibility of this type of steel to strain aging phenomena.

- Tempcore steels show the more stable behavior than other types of steel after heating up to 500 °C. The weakening of their mechanical properties is attributed mainly to the extensive tempering occurring above this temperature. To enhance their properties some alloying may be useful.
- Allooying the steel with manganese or with microadditions of vanadium provides higher strength to the core’s material, producing Tempcore bars that exhibit nearly constant tensile properties after heating up to 500 °C.

Acknowledgments

The Greek National Institute of Scholarships is gratefully acknowledged.

References


