

Fabrication of Reinforcement Bars in Unalloyed Steel

Abstract: Modern civil engineering requires increasingly many concrete reinforcing bars, necessitating the satisfaction of increasingly restrictive operational, design and investment-related requirements. As a result, design engineers and contractors, including welding engineers, deal with bars fabricated using various technologies affecting both the properties and the structure of bars. The article presents basic information concerning individual technologies used in the production of concrete reinforcing bars as well as their microstructure and mechanical properties.

Keywords: reinforcement bars, rolling, thermo-mechanical control process

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Introduction

The intense development of the building industry (see Table 1), particularly in relation to structures made of reinforced concrete, has translated into increasingly high requirements concerning the primary and indispensable element of each structure, i.e. the concrete reinforcement bar. Requirements formulated in relation to reinforcement bars include mechanical properties, weldability, geometry, the arrangement of ribs and adhesion to concrete. The above-presented set of requirements forced producers to search for technologies enabling the satisfaction of customers' requirements and ensuring appropriate fabrication profitability. The properties required in relation to concrete reinforcement bars can be obtained through the thermo-plastic forming of unalloyed

steels containing microagents, by cold hardening or through the hardening of surface layers of bars with their self-tempering during further cooling on the cooling bed. Presently, the latter method is dominant [1].

In addition to concrete enforcement bars made of unalloyed steel, increasingly many applications involved the use of bars made of

Table 1. Examples of structures containing reinforcement steel

No.	Investment	Country or location	Use of reinforcement steel [tons]
1	Three Gorges Dam	China	354,000
2	Rion – Antirion Bridge	Greece	57,000
3	Burj Khalifa	Dubai	39,000
4	Grand Coulee Dam	USA	35,000
5	Hoover Dam	USA	20,000
6	North Bridge	Warszawa	14,000
7	Bełchatów Power Plant	Bełchatów	9,500
8	City Stadium	Poznań	7,000
9	LNG Terminal	Świnoujście	5,300 for two vessels
10	AGORA Shopping Mall	Bytom	4,400

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stainless steel or composite bars. The above named materials are indispensable in structures exposed to corrosion phenomena or in structures where the use of ferromagnetic bars is impossible.

Technologies used in the making of reinforcement bars

Reinforcement steel is characterised by specific mechanical properties, identifying its usability and the range of applications in structures made of reinforced concrete. The obtainment of the high yield point of bars is possible using one of the technologies presented below [2]:

- rolling with the controlled temperature of bars made of unalloyed steels with additions of such microagents as vanadium or vanadium and niobium,
- heat treatment directly after rolling (accelerated cooling), performed using one of the following toughening methods: TEMPCORE, QTB THERMEX, TORSID or TERMOCOIL;
- cold hardening of bars through twisting, pulling and/or ribbing indentation.

The development of an appropriate technology enabling the fabrication of concrete reinforcement bars and ensuring the obtainment of a product characterised by specific mechanical properties, chemical composition, microstructure and weldability involves the following stages [3]:

- production of liquid steel in steelworks (steelmaking in the electric furnace and the processing of liquid steel in the ladle furnace),
- continuous casting of steel,
- transfer of continuous ingots to rolling mills and heating (or reheating) them before rolling,
- hot rolling of bars or wire rods,
- optional toughening of bars using an appropriate technology,
- final cooling of bars on the cooling bed.
- cold indentation of ribs on cold hardened bars (wire rods in coils).

Rolling with the controlling of the temperature of bars made of microalloyed steels

Concrete reinforcement bars can be rolled by slitting, i.e. the longitudinal cutting of a strip. To ensure cutting precision, the primary solutions necessitated the use of an initial strip characterised by the precisely dimensioned square-shaped cross-section. The sides of the square were concave to prevent its bulging (if any) after flattening in the subsequent roll pass, taking place on the flat face of a roller. However, the initial shaping of the bar so that it was square in cross-section and had sharp corners and concave side appeared unnecessary if a corrective edging pass was applied. Presently, the rolling sequence with shearing requires the following sequence of passes [1]:

- initial rolling of the flat bar having a width greater than the total of diameters of sheared strips and a thickness amounting to approximately 1.5 of the bar diameter,
- correction of the flat bar width in the edging pass,
- initial separation of the strip in a special pass (“dog’s bone”),
- shearing the strip in the pass and separating the strip using dedicated fixtures,
- separate rolling of each separated strip in the oval leading pass,
- rolling each strip in the finishing pass.

Figures 1 a and b presents exemplary calibration along with shearing in relation to the rolling of three bars having a diameter of 10.0 mm.

A strip having a thickness of 15.0 mm and a width of 34.0 mm (controlled by the edging pass) enters the pass as presented in Figure 1a (dog’s bone). The above-named pass is tasked with the initial arrangement of strips and the preparation of division planes (angles of inclination) adjusted to the tearing of strips at the subsequent pass (Fig. 1b). The elongation coefficient in the pass is corrected in the

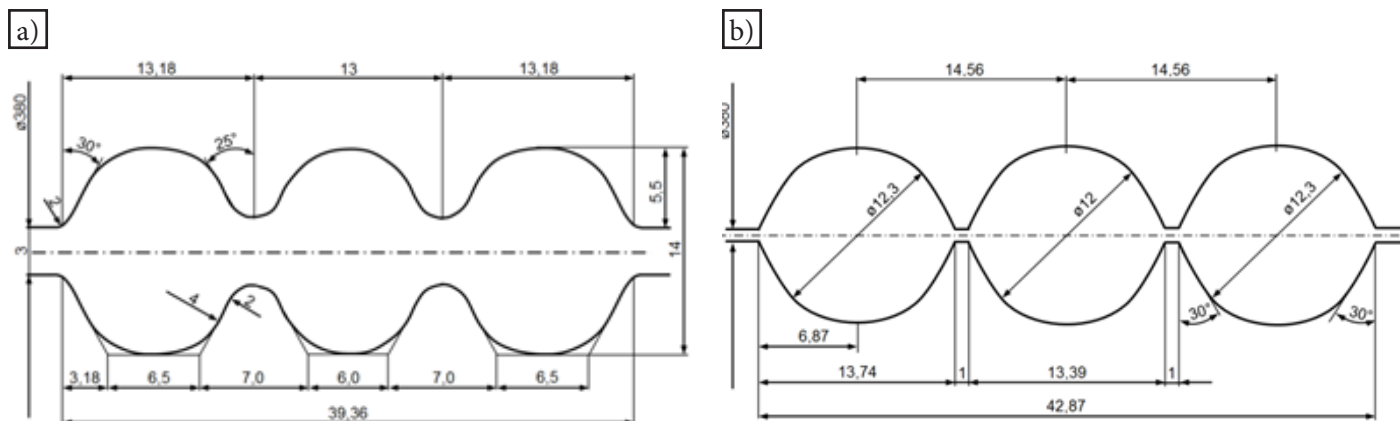


Fig. 1. Sequence of the shearing of the strip into three bars (ϕ 10.0 mm), a) separation of the initial flat bar, b) "shearing" before separation by means of special fixtures [1]

preceding edging pass. After leaving the edging pass (Fig. 1a), the strip enters slitting pass (Fig. 1b), where division into three initial round strips connected with bridges is obtained. The division is accompanied by the formation of planes (between shelves) being inclined at an angle (of 30°) smaller than the angle of the cone of the inserting roll (restricted within the range of 35° to 40°). The roller of the inserting guide rips the connecting bridges apart, leading to the obtainment of pseudo-circular strips (three), entering separately the leading oval and, after twisting, the finishing round pass with incised projections. Applicable technologies involve controlled rolling or rolling with toughening.

As regards controlled rolling, an increase in the yield point accompanied by a smaller increase in carbon equivalent C_e lower than in cases of such steels as 34GS (PN/-96/H 84023-6 [2]) can be obtained in relation to steel containing less than 0.2% of carbon with microadditions of chemical elements characterised by strong affinity for carbon and nitrogen (e.g. vanadium and niobium). Regular rolling consists primarily in identifying and maintaining the temperature of the last passes, reduced in comparison with that applied in the standard technology. Usually, the contents of alloying microagents do not exceed 0.2%. The application of the above-presented technology enables the obtainment of a yield point of 500 MPa, good plasticity and a carbon equivalent (CE) of less than 0.50%.

A steel grade enabling the obtainment of properties similar to those presented above is steel 20G2VY-b in accordance with the PN-89/H-84023/o6 standard. An example of steel characterised by a high yield point (above 500 MPa) as well as by good plasticity and weldability ($CE < 0.48\%$) is steel grade 16GV [3].

Hot rolling of bars with toughening

In state-of-the-art metallurgical processes, the charge used in hot rolling mills comes directly from continuous steel casting lines. The charge can be heated up to rolling temperature or it is possible to use hot continuous ingots. The use of hot continuous ingots as charges for rolling after reheating is economically beneficial and can improve the quality of products. Direct advantages are the following:

- lower consumption of energy used to heat the charge,
- reduced costs related to the transport and storage of ingots,
- reduced stock,
- increased efficiency of heat furnace,
- increased output resulting from the reduced amount of scale.

Energy savings resulting from the use of hot ingots are considerable. For instance, the use of ingots heated up to a temperature of 800°C instead of those of ambient temperature reduces the consumption of energy by the furnace by between 35 % and 40 % when heating the ingot to a temperature of 1200°C . In addition to

direct economic advantages, the use of hot ingots as the charge reduces stresses during heating and decreases the negative effect of copper on the quality of the rolled strip surface. The reduction of scale formation depth reduces the risk of copper cracking and moves the safe level of the copper content in steel upwards [4].

An exemplary technological line used for the hot rolling of bars is presented in Figure 2. During the process, if need be, the continuous ingot is heated up or reheated up to rolling temperature

in a walking beam furnace, scale is removed and the ingot is rolled in three rolling stands in the vertical/horizontal arrangement (initial group, intermediate group and finishing group). Before rolling it is necessary to remove scale (formed during heating) adhering to the charge surface. The above-named operation is necessary to prevent the contamination of charge surface by scale indented by rollers (so-called “lapped scale”). After rolling, the strip is cooled on a cooling bed enabling the performance of heat treatment involving rolling heat (e.g. QTB, TEMPCORE). After the heat treatment, bars are cooled to ambient temperature in the walking beam type cooling bed. After cooling, in cases of bars delivered in segments, bars are subjected to finishing procedures including straightening, cutting and making bundles [5].

The ultimate properties of bars made using the toughening process result from the shaping of their microstructure through hot straining and cooling directly after rolling. The bar cooling cycle is responsible for the formation of a

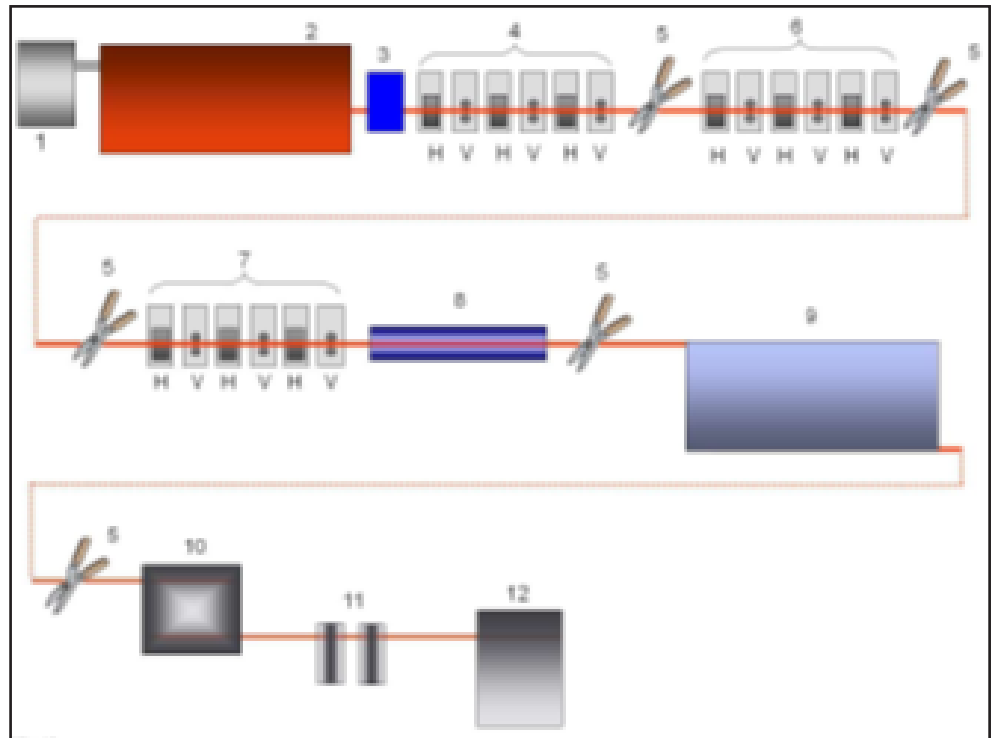


Fig. 2. Schematic diagram of a rolling mill making concrete reinforcement bars: 1) charging grid, 2) walking beam surface, 3) scale breaker, 4) initial group, 5) shear, 6) intermediate group, 7) finishing group, 8) water cooling group, 9) walking beam type cooling bed, 10) bundle forming machine, 11) saw and 12) terminal grid [5]

diversified microstructure in the bar cross-section. The above-named structure is composed of the subsurface layer of self-tempered martensite, the intermediate layer of bainite and the central area containing the ferritic-pearlitic structure. Figure 3 presents microstructural layers formed in bars made using the TEMPCORE method.

By changing the cooling cycle, i.e. the time and intensity of cooling, it is possible to significantly modify the volume fraction of individual layers and, consequently, the mechanical

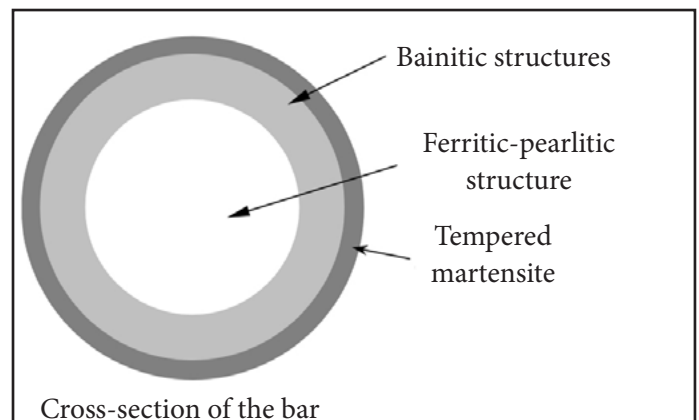


Fig. 3. Macrostructure of the reinforcement bar made using the TEMPCORE technology [3]

properties of rolled bars. The ultimate properties of the thermally hardened bar (under specific cooling conditions) depend on the microstructure of the bar before its entering the accelerated cooling system. In turn, the aforesaid microstructure depends on parameters of rolling, charge heating and the quality of continuous ingots.

The hardening of bars is primarily affected by the volume fraction of the martensitic layer. On one hand, the thickness of the martensitic layer is the function of the chemical composition of steel, whereas on the other, the function of the intensity and the time of cooling. An increase in the cooling rate is accompanied by a growing distance between the bar surface and the transition layer, in relation to which the temperature obtained during cooling corresponds to temperature M_s (martensite start), designating the boundary of the martensitic layer. Under constant cooling conditions, the depth of hardening (the thickness of the martensitic layer) depends primarily on the content of carbon as well as on that of alloying and doping elements, affecting the value of temperature M_s and the critical parameter of the cooling rate, i.e. the lowest cooling rate enabling the obtainment of the martensitic structure [4].

The effect of carbon should be considered in two aspects. On one hand, an increase in the content

of carbon decreases temperature M_s and, as a result, reduces the depth at which the martensitic transformation can take place. However, on the other hand, an increase in the content of carbon increases the hardening depth, resulting from increased steel hardenability obtained through the delayed start of diffusive (i.e. ferritic and pearlitic) transformations in relation to the range of the chemical composition of steel used for the making of TEC R bars. Under constant cooling conditions, an increase in the content of carbon eventually decreases the thickness of the hardened layer. In cases of certain primary and residual elements (Mn, Mo, Cr, V and Ni), their effect on the thickness of the martensitic layer is similar to that of carbon. The above-named chemical elements decrease temperature M_s and increase steel

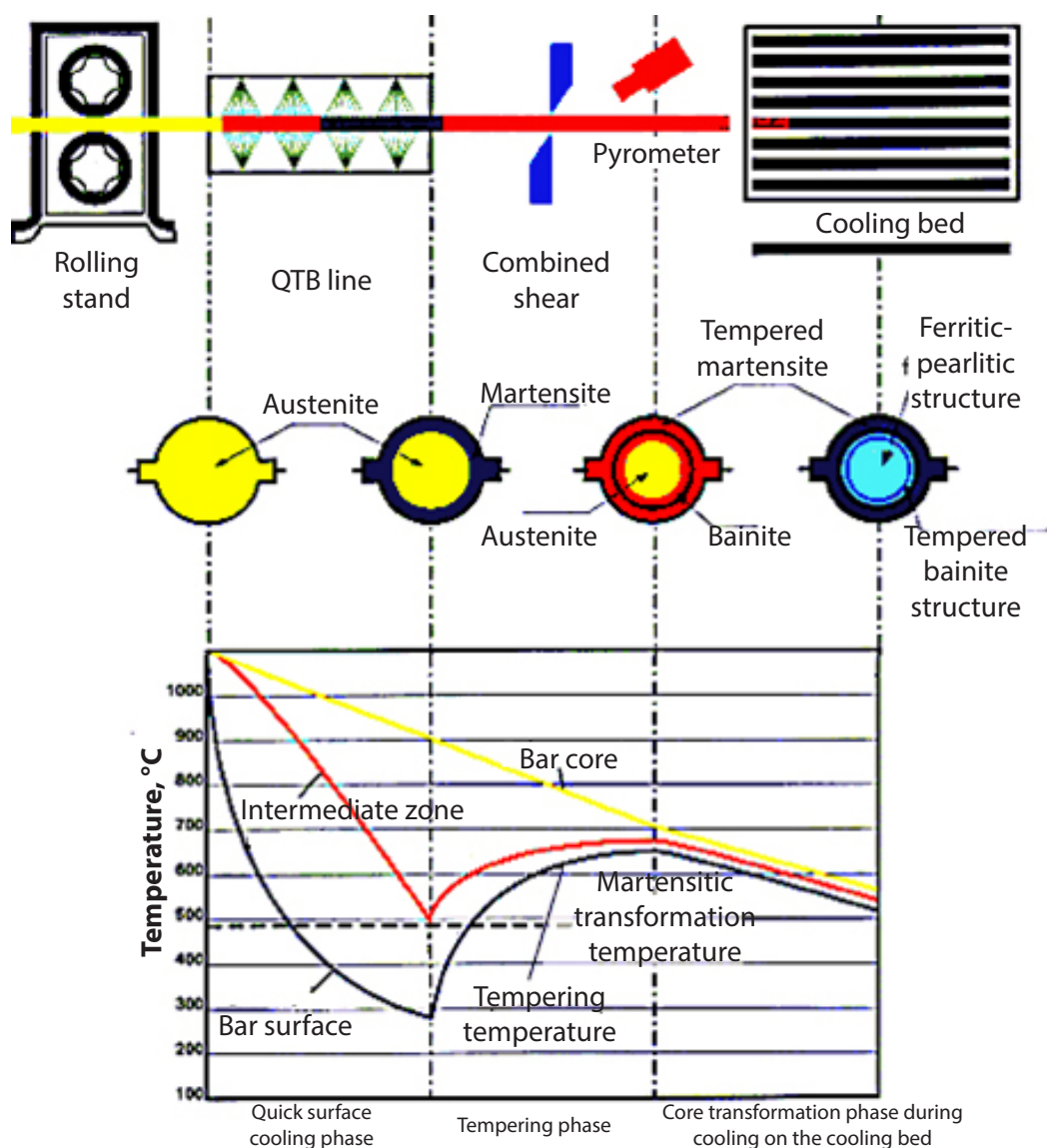


Fig. 4. Schematic diagram of the QTBT method (TEMPCORE) [6]

hardenability. In comparison with coal, the elements only slightly affect the value of temperature M_s , where their effect on the thickness of the hardened layer is primarily related to the effect in steel hardenability. An increase in the contents of Mn, Mo, Cr, V and Ni results in an increase in hardenability, and, consequently, an increase in the content of the martensitic structure and bainitic structure [4].

One of technologies used in the production of reinforcement bars and involving the toughening process is the Q.T.B. (Quenching and Tempering Bars) technology (being equivalent to the TEMPCORE controlled cooling method) developed by the DANIELI company. The technology enables the obtainment of higher mechanical properties of bars made of unalloyed steels by applying an appropriate system of the three-stage controlled cooling of bars in the hot rolling line. The method is presented schematically in Figure 4.

The first stage of the QTB process involves the intense cooling (with water) of a bar leaving the rolling stand. Because of the high intensity of water cooling, the rate of cooling affecting the bar surface is higher than the critical rate of martensite formation, leading to the obtainment of the appropriate depth of the martensitic layer on the bar surface.

The second stage starts once the bar has left the water cooling line and entered the zone of cooling in the open air. At this stage, heat from the hot bar core propagates convectively to the surface, triggering the self-tempering of the martensitic layer. The process of tempering provides appropriate material ductility without compromising the high conventional yield point.

The third stage takes place during the free cooling of bars on a walking beam type cooling bed and involves the semi-isothermal transformation of austenite in the bar core. In terms of its internal structure, a bar subjected to the above-presented heat treatment contains the subsurface layer of tempered martensite and

the bar core composed of ferrite, pearlite and intermediate structures [6].

The application of the QTB technology enables the obtainment of the following [6]:

- high tensile strength,
- favourable weldability resulting from the possibility of reducing the content of carbon without compromising the high conventional yield point,
- favourable formability during bending, without the formation of microcracks on the bar surface,
- very good operational characteristics of bars under fatigue conditions, obtained through the high plasticity of the surface layer of martensite, making QTB bars usable in structures exposed to dynamic loads,
- mechanical properties of QTB concrete reinforcement bars similar to those of bars made using the classical method.

Cold hardening of bars

The cold deformation of steel through pulling, twisting or rolling, is responsible for an increase in the yield point dependent on the size of distortion and the chemical composition of steel. The above-named technology is used for the making of drawn wires as well as smooth and ribbed bars having diameters not exceeding 16 mm (in practice below 12 mm). Cold hardening usually involves unalloyed low-carbon steels, e.g. St3S (PN-89/H-84023). The cold strain method enables the obtainment of high yield point (500 MPa) and strength (540 MPa), yet at the cost of reduced plasticity. In relation to yield point $R_{min}=500$ MPa, relative elongation A_{10min} stands at 8%. Figure 5 presents twisted bars, whereas Figure 6 presents upset bars (FILIGRAN) made of steel B500A (DIN 488-1 [7]).

Cold hardened bars are made directly from wire rods (in coils). Initial straightening is followed by rolling, usually involving the use of three knurled rollers (depending on customer's needs; see Fig. 7). The cold rolling of bars, involving the use of the set of rollers presented in

Figure 7 enables the obtainment of round bars (in cross-section), which is one of the primary advantages of the above-named technology. For technical reasons, the use of hot rolling or the thermo-mechanical control process leads to the fabrication of oval bars (Fig. 8), impeding or even precluding the making of, e.g. latticeworks. Table 2 presents the comparison of the properties of reinforcement bars made using various technologies.



Fig. 5. Twisted bars [8]



Fig. 6. Upset bars (FILIGRAN) made of steel B500A
a) supplied in coils, b) straight bars [9]



Fig. 7. Set of knurled rollers used in the production of cold hardened reinforcement bars a) unit featuring a set of rollers, b) knurled rollers [10]

Table 2. Comparison of the properties of reinforcement bars made using various technologies [11]

Fabrication manner	Treatment	Cost	Mechanical properties	
			Plasticity (elongation)	Weldability
Thermo-mechanical control process	Fast cooling and process control, cooling from rolling temperature	Low	Excellent	Low carbon equivalent, very good weldability
Hot rolling	Addition of alloying agents: C, Mn, V, Nb etc.	High	High	High carbon equivalent, limited weldability
Cold hardening	Cold straining	High	Low	Good weldability

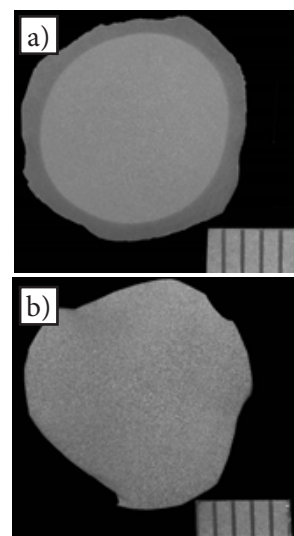


Fig. 8. Cross-sections of reinforcement bars, a) obtained through the TMCP (B500SP) and b) obtained through cold hardening (B500A)

Alloying agents in steels used for reinforcement bars

The mechanical properties of concrete reinforcement bars and their microstructural stability result from the precisely designed chemical composition of steel and appropriately developed manufacturing technology.

Providing steel with alloying agents is primarily aimed to [12]:

- obtain appropriately high mechanical and plastic properties,

- trigger specific changes in the microstructure,
- obtain special physical properties,
- increase hardenability,
- facilitate manufacturing technologies and improving heat treatment results.

One of the primary chemical elements affecting the properties of steels is carbon. An increase in the content of carbon is accompanied by an increase in tensile strength, yield point and hardness as well as by a decrease in toughness, elongation and area reduction. However,

Table 3. Effect of alloying elements used in steels on properties of bars [12, 13]

Chemical element	Properties of steels	Properties of bars
Carbon (C)	Hardness, strength, weldability, plasticity	The high content of carbon affects the strength of bars and increases the level of permissible stresses. A carbon content below < 0.1% reduces strength. A carbon content in excess of 0.3% is responsible for the unweldability and high brittleness of steel.
Manganese (Mn)	Strength, yield point	The higher content of manganese increases the strength of bars and, at the same time, increases the value of carbon equivalent.
Sulphur (S)	Impurities in steel responsible for brittleness	The content of sulphur should be limited. The higher content of sulphur is responsible for the brittleness of bars during twisting and rolling
Phosphorus (P)	Impurities in steel increasing susceptibility to cracking	High phosphorus content increases strength and corrosion resistance but at the same time favours the formation of low-melting phosphorous eutectics along grain boundaries and reduces toughness at sub-zero temperatures.
Copper (Cu)	Strength, corrosion resistance	Copper stabilises the pearlitic microstructure as well as increases mechanical properties and corrosion resistance.
Chromium (Cr)	Weldability, corrosion resistance	Chromium, usually obtained from steel scrap, affects the value of carbon equivalent, weldability and corrosion resistance.
Titanium (Ti)	Strength	Titanium improves strength and corrosion resistance as well as restricts the grain growth.
Vanadium (V)	Strength	Vanadium increases strength and hardness as well as restricts the grain growth and improves toughness.
Molybdenum (Mo)	Strength	Molybdenum increases strength and improves hardenability, particularly at higher temperature and in relation to changing loads.
Aluminium (Al)	Grain growth	Aluminium is used, among other things, for its denitriding and deoxidising properties.
Carbon equivalent (CE)	Hardness, strength, weldability	The parameter required when identifying technological parameters to be applied in the production of concrete reinforcement bars, e.g. using the TEMPCORE technology. The excessively high value of CE reduces the weldability of bars and their mechanical properties. In terms of bars made using the cold strain-based method (twisting, rolling) the value of carbon equivalent is reduced to 0.42%. In terms of bars made using heat treatment, directly after rolling the value of CE is not limited, provided that the properties of steel satisfy related requirements.

an increase in the content of carbon significantly reduces steel weldability [12]. Another chemical element significantly affecting the properties of steels is manganese, responsible for an increase in the hardness and strength of steels, at the same time reducing their plastic properties. Metallurgical processes also involve the adding of silicon, primarily used as a deoxidising element. Table 3 discusses the properties of individual chemical elements.

One of the primary reasons behind the adding of alloying elements to steels is an increase in mechanical properties combined with the simultaneous improvement in plastic properties. The maximum increase in the yield point, without increasing the temperature of transition into the brittle state, is obtainable in unalloyed, high-carbon and fine-grained steels containing the addition of aluminium, reducing the content of free nitrogen in steel by forming aluminium nitrides. An excessive increase in the content of aluminium leads to the greater amount of oxide inclusions in killed steel and the presence of plastic rolled MnS type II sulphides. The monitoring of grain size during hot plastic working and subsequent heat treatment is of great importance. In ferritic-pearlitic steels it is possible to obtain fine grains by continuing the reduced-temperature rolling process up to do 750°C. Lower temperatures at the end of the rolling of steels containing microagents of Nb, V and Ti result in the formation of smaller ferrite grains and higher yield point values. However, a decrease in the temperature at the end of the rolling process increases the temperature of transition into the brittle state, induced by the significant distortion of precipitated ferrite or precipitates of carbide coatings along ferrite grains. A decrease in the temperature at the end of the controlled rolling process slightly decreases the content of pearlite in the microstructure of steel.

Manganese is responsible for the refinement of ferrite grains and pearlitic colonies, at the same time increasing the yield point. As regards normalised or hot rolled steels used for the

making of concrete reinforcing bars, the content of carbon and that of manganese are often intentionally increased, yet at the expense of deteriorated weldability. In addition, an increase in the content of pearlite increases the temperature of transition into the brittle state (of steel), but only slightly changes the yield point in steels characterised by low carbon contents. By providing low-carbon steel with nitride or carbide-forming elements (Al, Ti, V, Nb or Zr restricted within the range of 0.01 % to 0, 2 %) it is possible to more effectively and rationally influence the mechanical properties and ductility of structural steel. The precipitation hardening of steel depends on the size, arrangement and the volume fraction of precipitates. Because of the fact that the size of carbonitride precipitates depends on plastic working and heat treatment, it is possible to obtain precipitates smaller than 100 nm, responsible for a significant increase in plasticity. In structural steels containing alloying microagents, significant importance is attributed to nitrides. An increase in the content of the aluminium microagent in steel is responsible (in addition to the presence of oxide inclusions and II type manganese sulphides) for the presence of unfavourable fractures in slowly cooled products. In addition to the favourable effect on the fine granularity of microalloyed steels, aluminium nitrides are also attributed with the unfavourable effect on mechanical properties (where the exceedingly high amount of nitrogen has been bonded in the form of aluminium nitride). In the above-presented situation, the further precipitation of dispersive nitride phase of the remaining chemical elements is impeded [14, 15].

In addition to aluminium, steels are provided with vanadium (characterised by relatively high affinity for nitrogen, responsible for both grain refinement and precipitation hardening). Precipitation hardening depends on the degree of the dispersion of vanadium carbonitride V(CN) particles, which, because of the high solubility of vanadium in austenite, can be formed in austenite during or after the transformation of

austenite into ferrite. Depending on the carbon content-nitrogen content ratio, steels are characterised by the greater precipitation of vanadium carbide (VC) or vanadium nitride (VN). In comparison with carbides, vanadium nitrides are characterised by lower solubility in ferrite and higher resistance to coagulation. Therefore, in relation to a given content of vanadium in steel, the precipitation of nitrides provides the greater effect of precipitation hardening. Precipitation hardening depends on a cooling rate applied after hot rolling. The kinetics of the precipitation of carbides and nitrides is as described below. Vanadium carbonitrides V(CN) rich in nitrogen constitute the dominant phase during the cooling of steel products in air. In relation to standard cooling rates used when cooling concrete reinforcement bars made of steels containing vanadium microagents, an increase in mechanical properties is related to an increase in the content of nitrogen in the form of carbonitrides. For this reason, in relation to steels characterised by

a higher nitrogen content used for the making of reinforcement bars, it is necessary to identify the optimum Al:N₂:V ratio in order to provide the maximum hardening of steel with grain refinement [14, 15].

An increase in the yield point obtained through the hardening of the solid solution of the matrix and precipitation hardening increases the temperature of transition into the brittle state. In turn, the obtainment of the analogous increase in the yield point through grain refinement reduces the temperature of transition into the brittle state. In addition, the obtainment of grain refinement to approximately 5 μm through the controlled rolling of steel with vanadium makes it possible to use the effect of precipitation hardening up to 142 MPa without increasing the temperature of transition into the brittle state [14]. Tables 4-10 present mechanical properties and exemplary requirements related to the chemical composition steels used form the making of reinforcement bars.

Table 4. Chemical composition, maximum values (% of weight) in accordance with PN ISO 6935 [16]

Steel grade	C ¹⁾	Si	Mn	P	S	N ²⁾	C _{eq} ¹⁾
RB 300 RB 400 RB 500	-	-	-	0.060 (0.070)	0.060 (0.070)	-	-
RB 400W RB 500W	0.22 (0.24) ³⁾	0.60 (0.65)	1.60 (1.70)	0.050 (0.055)	0.050 (0.055)	0.012 (0.013)	0.50 (0.52)

¹⁾In cases of grades RB 400W and RB 500W, in relation to bars having diameters in excess of 32 mm, the maximum content of carbon (C) amounts to 0.25% (0.27%), whereas the maximum value of carbon equivalent (C_{eq}) amounts to 0.55% (0.57%).

Carbon equivalent C_{eq} is calculated using the formula: $C_{eq} = C + \frac{Mn}{6} + \frac{(Cr + V + Mo)}{5} + \frac{(Cu + Ni)}{15}$,

where C, Mn, Cr, V, Mo, Cu and Ni represent contents of individual elements in steel in per cent of weight.

²⁾ Higher nitrogen content values are allowed, if contents of nitrogen-bonding elements are sufficient.

³⁾ Values in parentheses refer to the check analysis of a product.

Table 5. Required characteristic values of the upper yield point, tensile strength and the relative elongation of a specimen after rupture in accordance with PN ISO 6935 [16]

Steel grade	Upper yield point R _{eH} , N/mm ²	Tensile strength R _m , N/mm ²	Relative elongation A _{5.65} ¹⁾
RB 300	300	330	16
RB 400, RB 400W	400	440	14
RB 500, RB 500W	500	550	14

¹⁾ In Poland A₅ is used instead of A_{5.65}

Table 6. Chemical composition of steel in accordance with heat analysis¹⁾ in accordance with PN-89/H-84023/06/Ap. 1:1989 [2]

Steel grade designation	C ¹⁾	Mn ²⁾	Si ²⁾	P	S	Cr	Ni	Cu	Mo	N ₂	V	C _{eq} ³⁾
				max								
St0S-b	max 0.23	max 1.0	max 0.40	0,07	0,06	- ⁴⁾	- ⁴⁾	- ⁴⁾	- ⁴⁾	-	-	-
StSX-b	max 0,22	max 1,0	max 0,07	0,05	0,05	0,30 ⁵⁾	0,30 ⁵⁾	0,35 ⁵⁾	0,10 ⁵⁾	-	-	-
StSY-b	max 0,22	max 1,0	0,03÷0,15	0,05	0,05	0,30 ⁵⁾	0,30 ⁵⁾	0,35 ⁵⁾	0,10 ⁵⁾	-	-	-
St3S-b	max 0,22	max 1,0	0,10÷0,35	0,05	0,05	0,30 ⁵⁾	0,30 ⁵⁾	0,35 ⁵⁾	0,10 ⁵⁾	-	-	-
St50B	max 0,40	max 1,6	max 0,09	0,06	0,06	-	-	-	-	-	-	-
20G2Y-b	0,17÷0,23 ⁶⁾	1,1÷1,6 ⁶⁾	max 0,10	0,05	0,05	0,30	0,30	0,35	0,10	-	-	max 0,48
18G2-b	0,15÷0,22 ⁶⁾	1,0÷1,5 ⁶⁾	0,20÷0,55 ⁶⁾	0,05	0,05	0,30	0,30	0,35	0,10	-	-	max 0,48
25G2S	0,20÷0,29 ⁶⁾	1,2÷1,6 ⁶⁾	0,6÷0,9 ⁶⁾⁷⁾	0,04	0,045	0,30	0,30	0,35	0,10	-	-	max 0,58
35G2Y	0,30÷0,35 ⁶⁾	1,2÷1,6 ⁶⁾	max 0,08	0,05	0,05	0,30	0,30	0,35	0,10	-	-	max 0,59
34GS	0,30÷0,36 ⁶⁾⁸⁾	0,8÷1,2 ⁶⁾	0,4÷0,7 ⁶⁾⁹⁾	0,05	0,05	0,30	0,30	0,35	0,10	-	-	max 0,59
20G2VY-b	0,17÷0,23 ⁶⁾	1,2÷1,6 ⁶⁾	max 0,12	0,05	0,05	0,30	0,30	0,35	0,10	0,012÷0,02	0,05÷0,12	max 0,52

¹⁾ The content of arsenic in steel (check only on the Ordering's Party's request) cannot exceed 0.08%

²⁾ It is possible to exceed upper limits in relation to the content of carbon, manganese and silicon in the heat analysis of steel within the values of check analysis (of a product or half-finished product) in accordance with PN-89/H-84023/01, after satisfying requirements related to carbon equivalent C_{eq} (if required in relation to a given steel grade) as well as mechanical properties and technological conditions specified in Table 2.

³⁾ Requirements in relation to the carbon equivalent calculated using formula:

$$C_{eq} = C + \frac{Mn}{6} + \frac{(Cr + V + Mo)}{5} + \frac{(Cu + Ni)}{15}$$

apply to the chemical composition of steel in accordance with heat or check analysis.

⁴⁾ After agreeing on the order, the content of chromium, nickel and copper should not exceed 0.30% of each of the above-named elements, whereas the value of molybdenum should not exceed 0.10%.

⁵⁾ The content is not subjected to checking if the supplier guarantees conformity with requirements.

⁶⁾ The lower limits concerning the content of carbon, manganese and silicon apply to the burden material. If requirements concerning the mechanical properties and technological conditions (specified in Table 2) are satisfied in relation to products and half-finished products. with the consent of the Ordering Party it is possible to lower the lower limits of the contents of the above-named elements by values of lower deviations for check analysis in accordance with PN-89/H-84023/01.

⁷⁾ Upon the Ordering Party's request, after agreeing on the order, the content of silicon in accordance with heat analysis can be restricted within the range of 0.4% to 0.6%.

⁸⁾ In cases of continuously cast steels, the content of carbon can be restricted within the range of 0.28% to 0.36%.

⁹⁾ Upon the Ordering Party's request, after agreeing on the order, the content of silicon in accordance with heat analysis can be restricted within the range of 0.6% to 0.9%

In steel designation: St – steel, S – weldability, X – open-poured steel, Y – semi-killed steel, b – concrete reinforcement steel, G – manganese, in relation to grade II and III S – silicon (if its average content in steel does not exceed 0.5%), V – vanadium, numeral 2 after letter G signifies the mean content of manganese in steel, equal to or exceeding 1.3%

Table 7. Mechanical properties and test conditions in accordance with PN-89/H-84023/06/ Ap1:1989 [2]

Steel grade	Steel grade designation	Mechanical properties and technological conditions				
		Nominal diameter of wire rod or bar, mm	$R_e, R_{0.2}$ MPa	R_m MPa	$A_5, \%$	Bend angle α a – specimen thickness, mm d – mandrel diameter, mm
min	min					
A - 0	St0S - b	5,5÷40	220	310÷550 ¹⁾	22	$\alpha=180^\circ, d=2a$
A - I	St3SX-b		240	370÷460 ¹⁾	24	$\alpha=180^\circ, d=2a$
	St3SY-b					
	St3S-b					
A - II	St50B	6÷32	355	min 490	17	$\alpha=180^\circ, d=3a$
	18G2-b	6÷28		490÷620 ¹⁾	20	
	20G2Y-b			490÷620	20	
A - III	25G2S	6÷40	395	min 590	14	$\alpha=90^\circ, d=3a$
	35G2Y	6÷20	410		16	
	34GS	6÷28	410		16	
A - III N	20G2VY-b	6÷28	490	590÷780	13	$\alpha=90^\circ, d=4a$

¹⁾ It is possible to exceed the upper limit of R_m by 30 MPa after satisfying requirements related to the remaining properties.

Table 8. Chemical composition of steel grade B500SP in accordance with PN-H-93220:2006 [17]

Type of analysis	C	Mn	Si	P	S	Cu	Ni ¹⁾	C_{eq} ²⁾ max %
	Maximum content %							
Heat analysis	0.22	1.60	0.55	0.050	0.050	0.80	0.012	0.05
Check analysis	0.24	1.65	0.60	0.055	0.055	0.85	0.013	-

¹⁾ The exceeding of the above-presented values is allowed if per every increase of 0.001% N, the maximum content of P is reduced by 0.005%; the content of N in accordance with heat analysis should not exceed 0.015%

²⁾ Requirements related to the carbon equivalent calculated using the formula:

$$C_{eq} = C + \frac{Mn}{6} + \frac{(Cr + V + Mo)}{5} + \frac{(Cu + Ni)}{15}$$

Table 9. Mechanical properties – tensile strength in accordance with PN-H-93220:2006 [17]

Re ¹⁾ , MPa		R_m/R_e		$A_5, \%$	$A_{gt}, \%$
min	max	min	max	min	min
500	625	1.15	1.35	16	8

¹⁾ The upper limit of yield point R_{eH} is regarded as yield point R_e

Table 10. Steel grades, classification and characteristics of reinforcement bars in accordance with DIN 488-1:2009 [7]

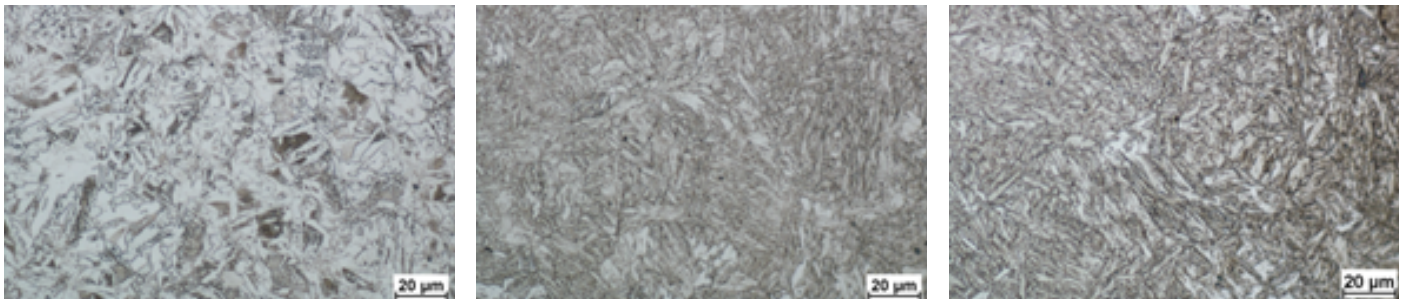
Steel grade	B500A	B500B	B500A	B500B	Quantile p (%) for W=1- α (one-sidedly)
Steel number	1.0438	1.0439	1.0438	1.0439	
Surface	ribbed		smooth (+G)	roll formed (+P)	
Product form in the as-delivered state	Reinforcement steel in coils, half-finished products, reinforcement mesh, lattice girders		Wire reinforcement in coils and bars, lattice girders		
Yield point R_e , MPa	500				
R_m/R_e ratio	1.05	1.08	1.05	1.05	5.0 for W=0.90
$R_{e,ist}/R_{e,nenn}$ ratio	-	1.30	-	-	10.0 for W=0.90
Total percentage elongation in relation to maximum force A_{gt} %	2.5	5.0	2.5	2.5	90.0 for W=0.90
					10.0 for W=0.90

Microstructure of concrete reinforcement bars

Depending on the chemical composition and the as-received state, the microstructure of steel used to make concrete reinforcement bars can contain ferrite, bainite, martensite or their mixtures. The microstructure of hot-rolled bars is the mixture of ferrite and pearlite.

In relation to strictly specified cooling cycles, the thermal hardening procedures involving bars made of steels characterised by a high yield point are responsible for the formation of a diversified microstructure (in the cross-section of the bar) composed of the subsurface layer of self-tempered martensite, the transitional layer of bainite and the central area composed of the ferritic-pearlitic microstructure. The example of microstructure present in bars subjected to the TEMPCORE processing is presented in Figure 9. The parameters of a cooling cycle, i.e. the temperature, time and intensity of cooling significantly affect the volume fraction of individual layers, and, consequently, the mechanical properties of a bar (related to the chemical composition of the steel heat, out of which the bar was rolled). If cooling parameters are stable, the properties of a toughened bar depend on its microstructure before entering the quickened cooling system. In turn, the above-named

microstructure depends on rolling parameters, the heating of the charge and the quality of continuous castings. A factor affecting the hardening of bars is the volume fraction of the martensitic layer. The thickness of the martensitic layer is the function of the chemical composition of steel as well as the intensity and time of cooling. An increase in the cooling rate is accompanied by an increase in the distance between the bar surface and the transition layer, in relation to which a temperature obtained during cooling corresponds to temperature M_s , determining the boundary of the martensitic zone. Under constant cooling conditions, the hardening depth (layer thickness) depends on the content of carbon and of alloying and doping elements affecting the value of temperature M_s and the value of the critical cooling rate, i.e. the lowest rate at which the martensitic structure can be obtained. An increase in the content of carbon decreases temperature M_s and, consequently, reduces the depth to which the martensitic transformation can take place. However, on the other hand, an increase in the content of carbon translates into the greater depth of hardening resulting from the increased hardness of steel being the consequence of the delayed start of diffusive, i.e. ferritic and pearlitic, transformations. Under constant cooling conditions, in



Bar centre, ferritic-pearlitic microstructure

Intermediate area, bainitic microstructure

Surface, tempered martensite

Fig. 9. Microstructure of the cold hardened concrete reinforcement bars made using the TEMPCORE technology, having a diameter of 32 mm

relation to the chemical composition of steels used for bars (TEMPCORE), an increase in the content of carbon is, in the aggregate, responsible for the reduction of the thickness of the hardened layer [4]. The bars are characterised by the uniform distribution of the above-named zones around the entire circumference. Hardness measurement results as well as results of hardness depth measurements revealed that the individual zones of the bars having the same diameter were characterised by similar thickness and hardness. Figure 10 presents hardness measurements results related to the cross-section of the bar.

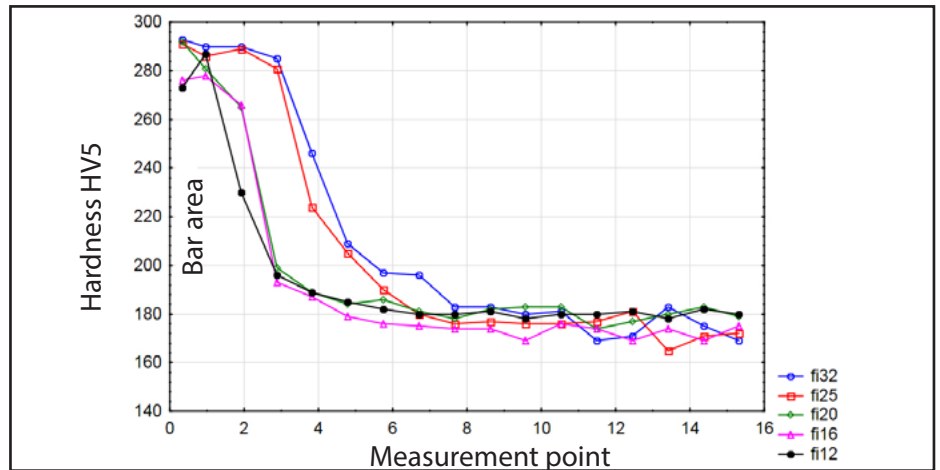
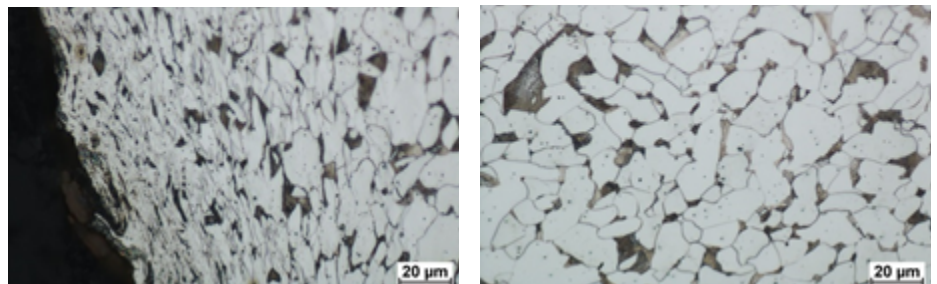


Fig. 10. Hardness measurement results related to the cross-section of cold hardened concrete reinforcement bars made using the TEMPCORE technology



External area of the bar

Central area of the bar

Fig. 11. Microstructure of the cold hardened concrete reinforcement bar having a diameter of 12 mm

Different microstructures are observed in bars made using the cold hardening technology, where the ferritic-pearlitic structure is present in the cross-section of the entire bar. However, in areas affected by rollers (Fig. 7) it is possible to observe significantly distorted individual grains (Fig. 11). As a result of cold squeeze, the hardness of steel increases up to 242 HV₅ (Fig. 12). As a result, cold hardened

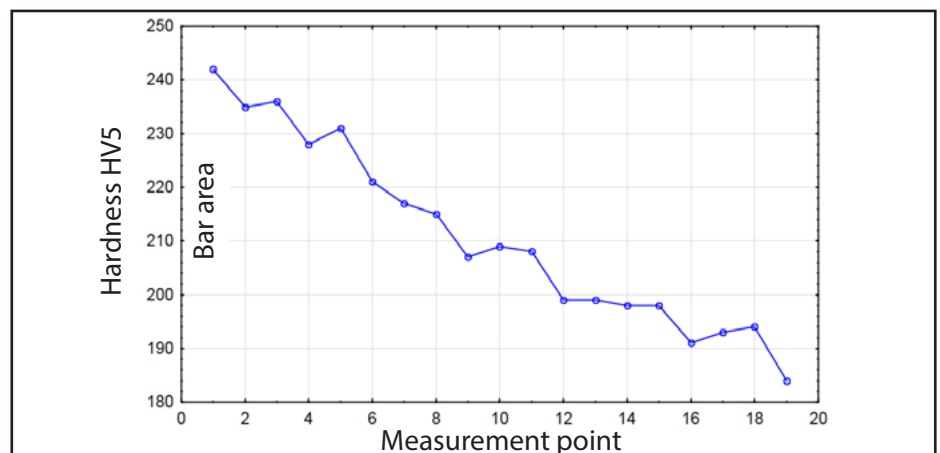


Fig. 12. Hardness measurement results in the cross-section of the cold hardened concrete reinforcement bar (Filigran)

bars are characterised by a yield point exceeding 500 MPa (B500A).

Summary

One of the most intensively developing sectors of Poland's economy is building engineering. Concrete reinforcing bars, commonly used in the building industry, are usually delivered in coils or as straight bars being up to 12 metres in length. If it is not possible to use continuous bars along the entire length of a given element, they can be connected, usually through overlap binding, by using anchoring loops or additional connectors as well as by using various welding methods. When making structures it is important to possess primary knowledge concerning the fabrication of bars and the effect of production technologies on bar properties. Both metallurgical and other treatment processes affect the weldability of bars made of unalloyed steels, which is of particular importance when making crucial structures such as bridges, overpasses, public utility buildings etc., the failure of which may result in financial losses or endanger human life. Damage to reinforced concrete structures arises from the lack of necessary theoretical and practical knowledge and failure to follow fabrication procedures, including those related to welding processes.

The article to follow will contain information related to composite bars and bars made of corrosion resistant steels.

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