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Comparative Structural Strength Research of Hardened Carbon Steel and Hot-Rolled Alloy Steel

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Abstract. Experiments on quantitative evaluation of fatigue strength showed that St5ps and St5sp carbon steels with A400 strength class can be fully applied for erection of constructions and buildings having cyclical loads during operation. Study of corrosion resistance of hardened carbon steel in comparison with hot-rolled alloy steel consists in difference in structures and hence, difference in intensity of electric and chemical processes featuring presence of steel in concrete. Structure of St5sp steel with A400 strength class in surface area has significantly less corrosion rate than ferritic-perlitic structure of 35GS steel with A400 strength class.

1. Introduction

Technology of combined stress and thermal hardening as any other meaningful idea has its perspectives offshoots. Studying microstructure and properties of hardened reinforced and angle section we paid our attention to the fact that sometimes when hardening based on interrupted tempering with subsequent self-tempering, strength mechanical properties of ordinary low-carbon steels are better than strength characteristics of alloy steels in hot-rolled state. For example, thermal hardening of bar section made of low-carbon steel allows to obtain rolled section which conforms to the level of mechanical characteristics of 09Mn2, 09Mn2Si alloy steels in hot-rolled state. Mechanical properties of low-alloy steels of this group after thermal hardening conform to strength class which meets properties of expensive nickel-containing 10CrSiNiCu types and 14Mn2NV steels with carbonitride hardening.

Besides, thermal hardening sharply increases cold resistance and impact strength level at temperature – 60°C exceeds 0.3 MJ/ m² [1,2].

As methodological basis of replacement of hot-rolled low-alloy steels by hardened low-carbon steels and expensive alloy steels by thermally hardened low-alloy steels an equal strength principle is accepted combined with analysis of stressed state and operation conditions of reinforced profiles. Study of temperature-time parameters of deformation processing of thermally hardened profiles made of 35GS low-alloy steels shows that there is possibility of its replacement by St3 and St5 low-carbon steels by thermal hardening. Study of chemical composition of 35GS, St5ps and St5sp steels demonstrates that manganese content in 35GS low-alloy steels is higher by 0.25-0.35%, and silicone - by 0.50% than in St5ps and St5sp steels with close content of carbon. Such increase in manganese and silicone content leads to higher resistance of undercooled austenite within temperature range from 400 to 600 ° C and as a consequence to increase of perlite component in the structure and hardening of



ferrite by means of dissolving of alloy components in it. It results in improvement of strength properties in these steels by 100 MPa in average with some reduction of its plasticity and weldability.

Experiments show that such strength improvement necessary for transformation of reinforced steel made of 35GS low-alloy steel into reinforced steel made of St5 low-carbon steel can be obtained by hardening thermal treatment without increase of manganese and silicone content [2].

Rapid development of industrial and civil construction in our country, especially in northern regions with severe climatic conditions as well as some cases of breakage of reinforced concrete constructions due to breakage of reinforced bars require to carry out study of structural strength of reinforced bars and work out additional requirements for properties.

2. Material and methods of researches

St5ps, St5sp, 35GS reinforced steels with profile diameter of 14 mm of Karaganda metallurgical complex (ArcelorMittal Temirtau) served as a material for the research. 14 mm diameter rebar was chosen based on the following factors: profile diameter of 14 is one of the popular minimum profiles which are the basis for manufacture of standard impact test sample of maximum section. Moreover, profile diameter of 14 is a middle profile out of rebar grades with diameter of 10-18 mm to be hardened up to A400 strength class. St5ps and St5sp carbon steel grades were hardened up to A-400 strength class using combined stress-thermal treatment in rolling process. Reinforced bars of hot-rolled low-alloy steels were used for comparative research. Mechanical properties (σ_B , σ_T and others) were determined according to standard method. Chemical composition and mechanical properties of steels used for structural strength studies are showed in the tables 1 and 2 below.

Table 1. Chemical composition of studied 35GS, St5ps and St5sp steel grades, %.

Steel grade	State	C	Mn	Si	Cr	S	P
35GS	Hot-rolled	0,31	1,12	0,86	0,19	0,034	0,023
St5sp	Thermal hardening	0,34	0,70	0,21	-	0,023	0,012
St5ps	Thermal hardening	0,35	0,77	0,15	-	0,036	0,014

Table 2. Mechanical properties of studied hot-rolled and thermally hardened steels.

Steel grade	State	σ_B , MPa	σ_T MPa	δ , %	Strength class
35GS	Hot-rolled	685	446	23,80	A400
St5sp	Thermal hardening	765	610	24,0	A400
St5ps	Thermal hardening	724	545	21,2	A400

It should be noted that evaluation of mechanical properties of metal materials shall be based on the following evaluation criteria [3].

1) Criteria determined with no reference to structural features and product service conditions.

2) Evaluation criteria of material structural strength. They feature material operation capability in operation conditions. These criteria are in full correlation with product service properties.

Strength and plastic characteristics of test samples with static loads were determined in the following range of temperatures: (+ 20°C) to (-70 °C). As stress risers contribute to brittle failure, especially at low temperatures, sensitivity of reinforced steels to presence of damages was studied. Besides, superficial damages which create stress concentrations were imitated with the help of sharp notches made on samples at the depth of about 0.05 % of profile nominal diameter with bending radius of $r=0.2$ mm. Given that longitudinal rib is the most protruded element of periodic profile it can be considered as the element exposed to different mechanical damages to the maximum extent. That's why 35GS reinforced steels with A400 strength class were evaluated to sensitivity and longitudinal rib of St5ps and St5sp steels with A400 strength class were evaluated to surface damages with static tension in temperature range of (+ 20° C) (- 60 °C). Notch on one of core longitudinal rib with 0.6 mm depth was made by hardness indentation with 0.15 mm spherical radius of the point.

Cold resistance of reinforced steels was studied based on test results of dynamic bending of prismatic samples with mild ($r = 1$ mm) notch. Tendency of steels to brittle failure was evaluated based on critical brittle point T_{crit} . determined by planimetry of viscous component in sample fracture.

Periodic profile of bar reinforcement providing sufficient cohesion with concrete creates local stress concentration in reinforcement bar and as a result it leads to reduction of bar fatigue strength. There is a significant impact of fillet radius of transverse projection with bar body on endurance limit of reinforced bars. Evaluation of endurance limit of steels studied was analyzed based on stress diagrams during cyclic tension regime.

Corrosion resistance of reinforced bars was determined not only in concrete and solution $Ca(OH)_2$ imitating liquid phase of cement brick but in environments which allow to toughen test conditions and evaluate impact of aggressive industrial environments with reference to behavior of reinforced bars (sulphates and chlorides). Impact of sulphates on corrosion of reinforced bars was determined using gravimetric method with 72-hours etching of cylindrical samples in 10% solution of sulphuric acid. Impact of chlorides on reinforced bars was determined using electrochemical characteristics of reinforced bars pressed into concrete by periodic moistening with 10 % solution of sulphuric acid. Electrochemical behavior of steel in concrete was studied using potentiometer by taking anodic and cathodic polarization curves and by registration of stationary potentials with time change.

3. Research results

Study of St5ps and St5sp carbon steel samples with A400 strength class and 35GS low-alloy steels with A400 strength class for static tension within the temperature range of (+20°C) - (- 60°C) showed that the values of temporary resistance and yield point rose by 50-75 MPa when temperature fell from - 25 to - 60.

Besides, yield point for 35GS steel with A400 strength class at - 60 °C reaches 500 MPa and 620-650 MPa for St5ps and St5sp steels with A400 strength class. Temporary resistance reaches values of 750 and 790-830 MPa accordingly. The results obtained show that during tensile test of samples at low temperatures properties of St5ps, St5sp and 35GS steels with A400 strength class change in fact equally. In addition, mechanical properties required by the standards are fully provided. Therefore, it is hardly to specify advantages of any of the above-mentioned steels.

Study of sensitivity of reinforced steels to damages creating stress concentration shows that damage of periodic profile has no impact on mechanical properties both at room and low temperatures while presence of stress riser on core body, especially on its longitudinal rib, causes considerable change of properties, especially at low temperatures. These tests demonstrated that St5ps and St5sp reinforced steels of A400 strength class are low-sensitive to notches on longitudinal rib and relative elongation reduces 1.7-2.0 times for 35GS hot-rolled steels and 1.3-1.5 times for thermally hardened steels.

It is known that metals and alloys with lattice structure depending on frost fracture threshold may display brittle breakage or viscous breakage. Frost fracture threshold is not a material constant component as it is greatly depends on its structure, stress concentrations, material size etc. Knowing frost fracture threshold and working temperature of material in operation it is possible to evaluate its temperature viscosity limit, i. e. temperature range between frost fracture threshold and working temperature. The more temperature viscosity limit, the less possibility of brittle breakage. As brittle and viscous nature of breakage during impact bending of steel can be identified based on fracture type, frost fracture threshold was determined according to fiber percentage (B %) of opaque, fibrous component in fracture. Number of fibers (B) in fracture was determined as ratio of area of fibrous (viscous) fracture to primary estimated sample section. According to curve with coordinates fiber percentage- test temperature, frost fracture threshold was determined, namely, temperature value at which fracture has 50 % of fiber which corresponds to KCU/2 impact strength.

Experimental data studied signify that application of St5ps and St5sp steels with A400 strength class instead of 35GS steels with A400 strength class for erection of reinforced concrete constructions operating in low temperature conditions of northern Kazakhstan will improve their sustainability.

Study of endurance of reinforced bars made of 35GS steels rolled on right and left mill streams through passes with different output demonstrates that wear of passes and increase of fillet radius of protrusions with core body virtually has no impact on strength characteristics and plasticity during static tension but leads to reduction of endurance limit by 8-10 %.

It should be noted that removal of stress risers (mechanically turned samples) allowed to avoid their impact and endurance limits obtained on mechanically turned samples of reinforced bars with different profile geometry have equal value.

It is established that fatigue strength characteristics of St5ps and St5sp thermally hardened carbon steel are equal to the same characteristics of 35GS A400 low-alloy steel. Based on the said experimental studies it can be concluded that St5ps and St5sp carbon steels with A400 strength class can be fully applied for erection of constructions and buildings having cyclical loads during operation.

35GS reinforced steel with A400 strength class is generally used as weld reinforcement for reinforced concrete constructions and has mechanical properties exceeding pre-planned estimated characteristics. However, there were cases when these constructions broke due to corrosion of reinforced steels although strength characteristics met GOST 5781 requirements. Therefore, there is a need to evaluate corrosion resistance of reinforced steels.

Reinforced steels can be regarded as resistant to stress corrosion fracture if during stresses of $0.9\sigma_r$ time to fracture exceeds 100 h. As tests based on these method showed, time to breakage of a sample made of St5 steel with A400 strength class loaded with 390 MPa amounted to 120 hours, i.e. reinforced steels with A400 strength class regarded as corrosion-resistant.

However, such evaluation of tendency to stress corrosion fracture cannot give full picture of steel corrosion resistance, especially in case of exposition to aggressive environments. It is known from practical experience that minor defects on metal surface can start damage of reinforced steels and spot corrosion reduces strength characteristics by 20-30%. Therefore, it is necessary to begin more detail study both of stress corrosion fracture and general corrosion of reinforced steels, work of galvanic couples appearing because of selective affection of metal surface by aggressive environments due to appearance of contacts between reinforced steels and aggressive environment during denuding of reinforced steels.

It is known that concrete is protective medium for reinforced steels and its corrosion starts after destruction of concrete or existence cracks in it. Protective properties depend both on chemical nature of concrete and its permeability for aggressive environments. As it was said, steel corrosion rate should be defined not only in solution $\text{Ca}(\text{OH})_2$ imitating liquid phase of cement brick but also in environments which allow to toughen test conditions and evaluate impact of aggressive industrial environments on reinforced steel behavior, in particular, sulphates and chlorides.

Sulphates present in most natural waters as well as in industrial waste waters. Sulphate solutions cause corrosion of concrete and reinforced concrete constructions which are in direct contact with

them. Chlorides present in concrete components and often are used as additives to speed up curing of concrete mix. Table 3 shows comparative data on corrosion rate of reinforced bars with diameter 14 mm with A400 strength class in different environments.

Table 3. Corrosion resistance of reinforced steel with A400 strength class.

Environment for corrosion test	Steel grade	Strength class	Corrosion rate, mm/year	Resistance grade according to the scale	Resistance category
H ₂ SO ₄	35GS	A400	0,37	2	Resistant
	St.5sp	A400	0,30	2	Resistant
NaCl	35GS	A400	1,28	3	Low-resistant
	St.5sp	A400	0,77	2	Resistant

As it follows from the above-mentioned data, in studied environment (H₂SO₄, NaCl) index of corrosion resistance of St5sp thermally hardened steel is better than that of 35GS hot-rolled steel. It can be seen that corrosion rate in 3% solution of sodium chloride, chosen as the environment for corrosion tests, in St5sp thermally hardened carbon steel is by 60% lower than that in 35GS silicone-manganese steel.

4. Results review

Combined deformation and thermal treatment of reinforced profiles made of St5sp and St5ps carbon steels provides improvement of strength properties up to level of GOST 5781 requirements for reinforced profiles made of alloy steels with A400 strength class. It follows herefrom that instead of reinforced profiles made of alloy steels with A400 strength class it is more effective and economic to produce equally strong reinforced profiles made of ordinary St5sp and St5ps carbon steels with A400 strength class.

However, presence of equal mechanical properties (σ_b , σ_T , δ_5) is not a required and sufficient basis for use of hardened carbon steels in reinforced concrete constructions instead of 35GS, 09Mn2Si alloy steels and others as strength, plastic and viscous characteristics defined by GOST 5781 neither reflect operation conditions and destruction nature during operation nor stressed state of reinforced bars of periodic profile. Therefore, based on mechanical properties defined by GOST 5781, it is actually impossible to establish which of these steels are better in real operational conditions. Hence, there are actuality and academic and research importance of study of structural strength of these steels.

Strength study at low temperatures demonstrate that during tensile tests of samples at low temperatures mechanical properties of hardened carbon and alloy steels with A400 strength class change in fact equally. In addition, values of mechanical properties required by the standards are fully provided. Therefore, it is hardly to specify advantages of any of the above-mentioned steels even at low temperatures [4].

Evaluation of sensitivity of reinforced steel with A400 strength class to surface damages shows that presence of notch does not result in considerable change of strength property values of hardened and hot-rolled steels and change nature with temperature fall from -20°C to -70°C . However, as the experiments demonstrated, during testing of samples with notches, 14 out of 15 samples made of 35GS steel with A400 strength class were broken whereas number of broken samples made of St5sp steels with A400 strength class amounted to only 7 and only 8 for St5ps steels with A400 strength class, i. e. if during testing of samples with notches virtually all samples made of hot-rolled steels were

broken then during testing of samples made of thermally hardened steels only half of them were broken.

Presence of notches on samples leads to significant reduction of relative elongation of 35GS hot-rolled steels: from 24-25% to 12-15%. Relative elongation of samples made of hardened steels broken on base metal is equal to elongation of samples without notches. In cases when samples were broken because of notches there was reduction of relative elongation of St5sp steels from 20% to 15%, and to 12% for St5ps steels. According to plastic characteristics, hot-rolled steels in comparison with thermally hardened steels seem to be more sensitive to notch. Samples made of thermally hardened steels given the presence of notches broke with plastic deformation. Test data showed that St5sp and St5ps steels with A400 strength class are low-sensitive to notches on longitudinal rib. Moreover, notches on longitudinal rib cause significant reduction of relative elongation of 35GS hot-rolled steels and less significant one for steels with A400 strength class.

During evaluation of structural strength of reinforced bars in reinforced concrete constructions intended for operation at low temperatures the data of dynamic impact bending tests of bar samples were used. However, during evaluation of behavior of reinforced bars at low temperatures, impact tests shall be accepted as quite conditional due to significant difference between stressed state in impact sample and in real reinforced bar.

As working reinforced steel made of reinforced concrete constructions is mainly undergone to tensile and compressing stresses, crack resistance evaluation method shall be accepted as main criterion during evaluation of reinforced steels [5].

Widespread application of reinforced steels in reinforced concrete constructions which undergone repeated loads also generates a need for study of reinforced steels for endurance. Steel sensitivity to stress concentration was studied using effective concentration coefficient which is a ratio of endurance limit of smooth sample to stress limit. While evaluating sensitivity of reinforced steels to stress concentrations it should be concluded that 35GS, St5sp and St5ps steels have similar stress concentration coefficient equal to 1.77; 1.76 and 1.74 accordingly. This is due to presence of close structures in mechanically turned samples made of 35GS hot-rolled steels and St5sp and St5ps hardened steels.

Microfractographic study of fracture surfaces showed that fatigue damages of 35GS low-alloy steels St5sp and St5ps carbon steels have equal nature. The results obtained confirm available data about the fact that the important factors featuring endurance of reinforced bars are geometric parameters of periodic profile of reinforced steel [6,7].

Corrosion is an electrochemical process because anodic (oxidizing) and cathodic (reducing) reactions are referred to processes with electrons transmission [8].

Table 4. Data on galvanic corrosion microcouples.

Galvanic corrosion microcouples	Anode (oxidant)	Cathode (reducer)
	Area with big energy	Area with less energy
Perlite	Ferrite	Cementite
Grain boundaries	Grain boundaries	Grain body
Fine and coarse grains	Fine grains	Coarse grains
Structural imperfections	Defects (dislocations, vacancy defects etc.)	Perfect structure
Deformed areas	Deformed and phase hardening areas	Annealed metal or alloy
Stress areas	Loaded areas	Non-loaded areas

Imperfect structures serve as anodes because adjacent areas have excess deformation energy and process of oxidation of atoms of these adjacent areas to ions requires less additional energy. In case of

heterogeneous structures phase compositions as a rule differ greatly. For example, if ferrite composition (carbon content 0.006 %) and cement (6.67 % C) in perlite is not equal, then they have different electrode potentials and form microgalvanic couple.

Improvement of corrosion resistance of thermally hardened steel in comparison with 35GS hot-rolled low-alloy steel consists in difference of structures and hence, in difference of intensity of electric and chemical processes featuring presence of steel in concrete. As it is known, heterogeneous structures are less resistant to corrosion attack than homogenous structures as solid solutions. In heterogeneous structures this is due to the fact that matrix works as an active anode and inclusions or particles of second phase work as a cathode. Besides, cathode activity considerably depends on shape and dispersiveness of impurities. For example, laminated structures have more high resistance to corrosion attack in comparison with grain structures. Troostite structures have minimum corrosion resistance [9,10]. Apparently, it is due to significant dispersiveness of carbide constituent in troostite structures which increases number of anode-cathode microcouples. Increase of tempering temperature leading to coagulation of cementite (carbide constituent) as well as to removal of internal strains originated during quenching reduces tendency to corrode.

Structure of St5sp thermally hardened steel of A400 strength class in surface area (secondary sorbite) has far less corrosion rate than ferritic-perlitic structure of 35GS steel with A400 strength class. Besides, it should be noted that ferritic-perlitic structure of 35GS steel is more electrochemically heterogeneous and rate of anode and cathode processes which determine corrosion resistance is considerably higher than in more equilibrium structure of St5sp steel with A400 strength class having different structure at the surface area and in the core center. Thus, while studying corrosion resistance of hardened steels it should be taken into consideration the difference in microstructure based on core diameter. If there are signs of crack origin on the surface then its growth and distribution depends on corrosion resistance of layers following surface hardened ring. This poorly studied question requires further study.

Increased resistance observed to corrosion of St5sp and St5ps steels in comparison with 35GS steels shows that obtainment of structural states close to balanced ones due to thermal hardening contributes to increase of corrosion resistance.

5. Summary

1. Results obtained demonstrate that while tensile testing of samples at low temperatures, properties of hardened carbon steel and hot-rolled low-alloy steel with A400 strength class change in fact equally. In addition, mechanical properties required by the standards are fully provided. It is established that in fact damage of transversal rib of periodic profile has no impact on mechanical properties both at room and low temperatures while presence of stress riser on core body, especially on its longitudinal rib, causes considerable change of properties, especially at low temperatures.

2. Given the more high values for impact bending, thermal hardening of carbon steels provides shifting of cold-shortness curve towards low temperatures as compared to 35GS hot-rolled steel. Analysis of critical temperatures of cold resistance T_{crit} and notch sensitivity demonstrates that St5sp reinforced steel with A400 strength class has cold-shortness threshold by 60°C less than that of 35GS reinforced steel of the same strength class. Application of St5sp and St5ps steel instead of 35GS steel for manufacture of reinforced concrete constructions operating in low temperature conditions of northern Kazakhstan will improve their sustainability.

3. It is established that fatigue strength values of St5sp and St5ps thermally hardened carbon steel are equal to the same characteristics of low-alloy steel of the same steel strength class. St5sp and St5ps carbon steels with A400 strength class can be fully applied for erection of constructions and buildings having cyclical loads during operation.

4. Corrosion resistance characteristics of thermally hardened steels have become better than that of 35GS hot-rolled steels. Comparative analysis demonstrates that St5sp and St5ps steels have positive potential for reinforced steel, less area of affected surface, low porosity of general corrosion and what is more important – considerably less size of corrosive holes which can initiate crack origin.

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