MECHANICAL BEHAVIOR OF MILD LOW-CARBON STEELS AFTER PLASTIC DEFORMATION AND HEAT TREATMENT

Rossen RADEV, Danail GOSPODINOV, Mariana ILIEVA, Nikolay FERDINANDOV, Ivo DRAGANOV

University of Ruse, Ruse, Bulgaria, EU, rradev@uni-ruse.bg, dgospodinov@uni-ruse.bg, mdilieva@uni-ruse.bg, nferdinandov@uni-ruse.bg, iivanov@uni-ruse.bg

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Abstract

One of the major benefits of low-carbon steels is their cost-effectiveness which makes them a preferable choice for a wide range of applications. In this study mechanical behaviour of mild low-carbon steels is investigated, especially the change of yield strength and tensile strength after plastic deformation and a specific type of heat treatment - firing of enamelled steels.

Furthermore, the present work includes investigations about opportunities for computer simulations and prediction of changes in mechanical properties. The obtained results were compared to experimental ones and discussed.

Keywords: mild low-carbon steel, mechanical properties, heat treatment, firing of enamel

1. INTRODUCTION

Mild low-carbon steels are a type of steels that contain a relatively small percentage of carbon - typically less than 0.25 %. They are widely used because of their high toughness, excellent ductility, very good weldability, strength, suitable for many applications, and good machinability. Typical uses of these steels include automotive body panels, structural shapes (beams, channels), tubes and piping, fasteners such as bolts and nuts, and machine parts where high strength is not critical.

Many manufacturers of thin-walled pressure vessels and water heater storage tanks use low-carbon steels for their products too. Usually, these products have requirements for enamelling. Enamelling steels are specially designed or treated steels that allow vitreous enamel to adhere well during firing, without defects like fish-scaling or poor adherence. Frequently used direct-on enamelling steels are intended for direct application of enamel onto the steel surface. Such kind of steels are aluminium, or silicon killed steels as well as steels with added Ti, Nb, B, Mn [1-6]. They are characterized by low carbon content to prevent hydrogen blistering, and fine, homogeneous grain structure. Despite being specially developed for enamelling, the use of these steels is not preferred due to economic considerations.

The pressure vessels are subject to safety requirements to ensure minimal permanent deformation when the tank is under static pressure load. Meeting these requirements implies sufficiently high values of the yield strength of the steels used for their manufacture. In the case of enamelled water heaters production, the requirements for high values of the yield strength are determined not only by the need for structural strength of the vessels but also by requirements for lack of enamel defects. The enamelling process involves applying one or more layers of enamel to a previously prepared surface of a of steel and then drying and firing it at a temperature above the softening temperature of enamel. Typically, firing temperature is between 780 °C and 850 °C. Firing is carried out in a furnace with oxidising atmosphere. Firing time and temperature depend on the thickness of the steel and the type of enamel.

The suitability of a particular steel to satisfy the need for structural strength of the vessels and the requirements for lack of enamel defects is determined by the enamel-fire annealing (EFA) process. This process requires heat treatment of the pressure vessels in the range of 800 – 900 °C and has direct impact on mechanical properties of vessels steel, especially on values of the yield strength.

Several researchers have studied the influence of the enamel-fire annealing process on the yield strength of enamelling steels. Jiang et al. investigated decreasing of yield strength of cold rolled enamelling steel sheets [7] and cold and hot rolled enamelling steels [8]. Authors of [9] report that increase of soaking temperature and holding time leads to an increase in the yield strength and tensile strength after EFA simulation for high strength hot rolled sheet steel for electrostatic enamelling. Zhang et al. [10] investigated two grades of hot rolled steel plates, developed to satisfy the requirements of enamelling. The first one is industrial hot rolled steel with carbon content in range of 0.10 – 0.20 mass % and content of Mn reaching up to 1.2 mass %, while the second steel, with added V, Ti and Nb, was specially designed and manufactured in the laboratory. For the first investigated steel, a slight increase in the values of the yield strength was found, without significantly changing the tensile strength. For the steel specially designed for enamelling, there was a decrease both in the yield strength and the tensile strength.

Summarizing the above, there are studies in the specialized literature on the mechanical behaviour and microstructure of steels specially intended for enamelling. These steels are characterized by a decrease in the yield strength because of enamel-fire annealing process. This is a prerequisite for the destruction of structures made of these steels after loading or for the destruction of the enamel coating. Information on the influence of the EFA process on the mechanical behaviour, particularly the yield strength, of common low-carbon steels has not been widely discussed. This is probably due to the assumption that low-carbon steels are not suitable for the manufacture of mechanically loaded enamelled products.

The present study focuses on the effects of enamel-fire annealing on the mechanical properties and microstructure of the mild low-carbon steels.

2. EXPERIMENTS

For the purposes of this study, samples of two grades of rolled steel sheets were used, steel A and steel B respectively. Their chemical compositions, determined after examination with an optical emission spectrometry analyser SPECTROMAXx DCM 2752, are presented in the **Table 1**.

Table 1 Chemical compositions of the investigated low-carbon steels

Steel A	Chemical element	C	Si	Mn	P	S	Al	N	Fe
	wt%	0.066	0.062	0.478	0.011	0.0063	0.028	<0.010	Balance
Steel B	Chemical element	C	Si	Mn	P	S	Al	N	Fe
	Wt%	0.047	0.063	0.463	0.0084	0.0064	0.039	<0.010	Balance

To obtain the information about the change in microstructure and mechanical properties of the enamelled and fired steel samples (both of Steel A and Steel B sheets), a physical simulation heat treatment experiment has been designed and used. The parameters of the simulated enamelling process were representative for the manufacture of water tanks for electric water heaters – firing temperature T = 850 °C and soaking time in furnace t = 30 min. After the soaking, the samples were taken out of the furnace and cooled in air. Substantially, the firing process is a normalizing heat treatment. The physical simulation heat treatment experiment described above was used for two different cases. The first one was for the physical simulation of enamelling of metal sheets in the as-rolled condition (Case 1) and the second one - for metal sheets that have undergone plastic deformation (Case 2) with strains ε corresponding to the real strains in the process of deep drawing of the bottoms for water tanks for electric boilers - ε = 15 %. Throughout the following, mechanical property values are shown as average values from multiple experiments.

The microstructure of steel substrates was examined by Carl Zeiss Jena optical microscope. The mechanical properties were tested by Instron 3384 universal tensile machine.

3. RESULTS AND DISCUSSION

The mechanical properties of the two investigated as-rolled steel sheets are shown in **Table 2**.

Table 2 Mechanical properties of as-rolled steel sheets

Steel A			Steel B		
Tensile strength (R_m) [MPa]	Yield strength (R_e, $R_{p0.2}$) [MPa]	Elongation (A_{80}) [%]	Tensile strength (R_m) [MPa]	Yield strength (R_e, $R_{p0.2}$) [MPa]	Elongation (A_{80}) [%]
381.0	294.3	32.4	352.6	292.0	35.5

The changes in tensile strength and yield strength caused by the physical simulation of enamel firing are shown in **Table 3**. Case 1 corresponds to a specimen without prior plastic deformation, while Case 2 refers to a specimen that was deformed up to strain ε =15 % and then fired.

Table 3 Changes in tensile strength and yield strength for different Cases of studied steels sheets

Steel A	Tensile strength (R_m) [MPa]	Yield strength (R_e, $R_{p0,2}$) [MPa]	**Steel B**	Tensile strength (R_m) [MPa]	Yield strength (R_e, $R_{p0,2}$) [MPa]
Case 1 without plastic deformation	371.0	324.8	Case 1 without plastic deformation	338.3	244.7
Case 2 after plastic deformation	346.8	288.1	Case 2 after plastic deformation	269.2	142.3

As a result of physical simulation of the above-described varieties of physical simulation (Case 1 and Case 2), changes in the values of tensile strength and yield strength occurred in the samples of the tested steel sheets, shown in **Figure 1**. For steel A, the firing simulation without preliminary plastic deformation showed a decrease in the tensile strength values and a slight increase in the yield strength. Regarding the yield strength, at first glance its increase during enamel firing process simulation seems strange, but other authors have reported similar results too [9]. In the variant in which the tested specimen had undergone plastic deformation (Case 2), a decrease in both the tensile strength and yield strength values was observed. For steel B, both the tensile strength and yield strength were reduced. It is noticeable that the yield strength decreased when the enamel was fired after plastic deformation. This is disturbing as the production of pressure vessels usually requires deep drawing technological operations. Such operations, combined with subsequent enamel firing, can be a prerequisite for damage to occur because of the operation of the vessels.

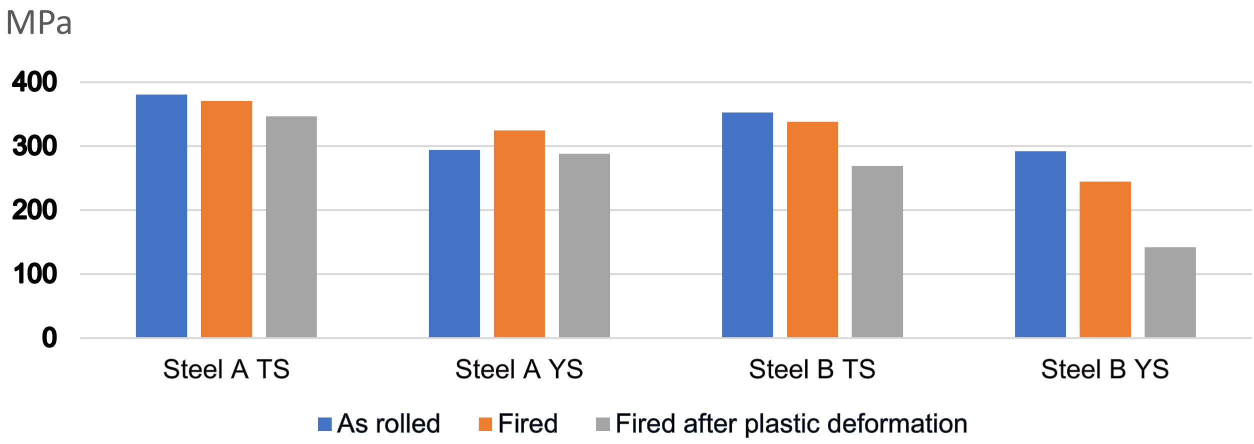


Figure 1 Tensile strength (TS) and yield strength (YS) for different Cases of studied steels sheets

The observed microstructure of both steels in the as-rolled condition was homogeneous. The crystal grains were equiaxed with size of 0.006 – 0.025 mm for steel A and 0.010 to 0.065 mm for steel B. The shapes and size of the crystal grains of steel A did not change significantly after the physical simulations for both Case 1 and Case 2. For steel B, there was a significant change in the shape and size of some grains during physical simulation of enamel firing with the larger ones located near the surface of the crystal sheet. This is especially evident for Case 2 - firing simulation after plastic deformation, shown in **Figure 2.** Since the decrease in yield strength is mainly due to an increase in grain size and a decrease in dislocation density, the coarsening of the crystal grains corresponds to the change in tensile strength and yield strength. The appearance of larger crystal grains during enamel firing was facilitated by the prior deformation up to strain ε =15 % - close to the critical one, at which grains of maximum size could be obtained.

Steel B as-rolled

Steel B firing after plastic deformation

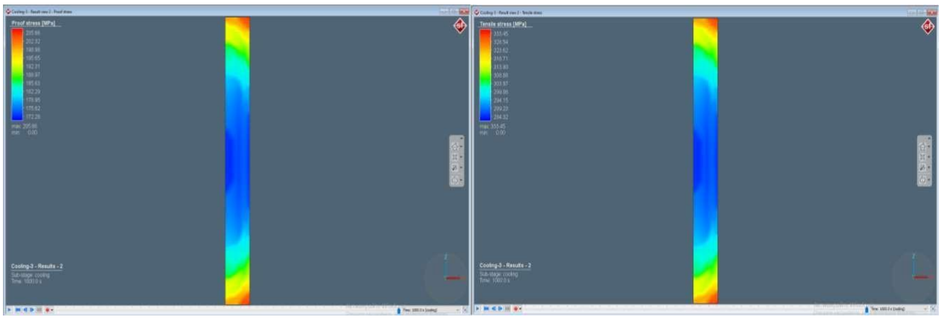
Figure 2 Microstructure evolution of steel B at physical simulation of firing after plastic deformation

To establish the possibility of predicting the change in the mechanical properties of low-carbon steel substrates during enamelling, numerical simulations of enamel firing were conducted as part of this study. To simulate the enamel firing process, Simufact Forming 14 software for simulating forming and heat treatment processes was used. The software allows to simulate the change in temperature as a function of time at each point of the volume of the studied objects, magnitude and distribution of stresses, deformations, etc. Simufact Forming provides support in material flow stress calculations and prediction of material properties, too. The material model used for computer numerical simulations was generated by JMatPro version 7.0, based on the chemical composition of steels A and B and data on the size of their crystal grains in as-rolled condition. In the context of the suitability of a particular steel to satisfy the need for structural strength of the vessels and the requirements for non-destruction of the enamel, additional studies are relevant for steel B, due to its poorer mechanical properties.

The obtained from the computer simulation of Case 2 for steel B results for tensile strength and yield strength were compared with those previously obtained after physical simulation. They are shown in **Table 4** and illustrated in the **Figure 3**.

Table 4 Tensile strength and yield strength obtained after physical and numerical simulation of studied metal sheets from steel B for Case 2 (after plastic deformation)

Steel B	Tensile strength (R_m) [MPa]	Yield strength (R_e, $R_{p0,2}$) [MPa]
Case 2 physical simulation after plastic deformation	269.2	142.3
Case 2 numerical simulation after plastic deformation	264.3	172.3



a) b)

Figure 3 Tensile strength (a) and yield strength (b) after numerical simulation of sheets of steel B for Case 2

As can be seen in **Table 4**, the values obtained for the tensile strength after physical and numerical simulation of the enamel-fire annealing (EFA) process are very close. The values of the yield strength differ by more than 20 % and are higher for the numerical simulation.

4. CONCLUSION

The research described in this publication is aimed at investigating the possibilities of using mild low-carbon steels for the manufacturing of enamelled pressure vessels. The two studied steels A and B have a similar chemical composition, differing mainly in the carbon content. The other difference that has been established is in terms of the size of the crystal grains in the as-rolled condition. Steel B is characterized by a coarser grain structure.

The enamel-fire annealing process is the cause of the change in the mechanical properties of the studied steel sheets. For both steels there is a decrease in strength, which is more pronounced for steel B. The yield strength for the case of the EFA simulation shows a slight increase for steel A and heat treatment without preliminary plastic deformation (Case 1) and no change in the initial value when simulating enamel firing after plastic deformation (Case 2). For steel B, the yield strength decreases, and for Case 2 this is quite pronounced - more than two times compared to the as-rolled condition.

The mechanical tests, physical and numerical simulations of the enamel-fire annealing process for the two cases - without preliminary plastic deformation (Case1) and after plastic deformation (Case 2) of the studied samples, allow the following conclusions to be drawn:

- The yield strength reduction after enamel-fire annealing results primarily from an increase in grain size.
- To prevent accidents during the operation of enamelled pressure vessels made of mild low carbon steel, these vessels have to be designed considering the reduction in the yield strength due to the forming and enamel firing operations during their production.
- Additional research is needed to improve the material models of low-carbon steels to ensure adequate simulation of their behaviour during production processes.

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