THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N°. 1 - 2018, ISSN 1453-083X

RESEARCH ON THE INFLUENCE OF CHEMICAL COMPOSITION AND STRUCTURAL CONDITION ON THE PROPERTIES OF HIGH-RESISTANCE NAVAL STEEL FLAT ROLLED PRODUCTS

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ABSTRACT

The performance achieved in the manufacture of large ships and components of special characteristics requires the use of quality metallic materials with physico-chemical and mechanical characteristics able to satisfy the quality conditions specified in the product standards for a safety operation.

The category of flat rolled products widely used in naval industry includes the high-strength sheet steel whose characteristics depend on the correlation of the chemical composition with the thermal and / or the thermo-mechanical processing in order to obtain the prescriptions imposed by the naval regulations.

The paper presents some of the experimental results obtained by a laboratory scale research program for the study of the influence of the thermal and / or thermomechanical treatment parameters on the use characteristics of the high-strength naval steel sheet while ensuring the constancy of these characteristics in the manufacturing. The evaluation of the physical-mechanical properties and the interpretation of the experimental results obtained have as reference similar properties obtained from conventional thermal processing or even from the state of rolling as the state of the product delivery.

KEYWORDS: steel, rolled, heavy plates, temperature, structures, mechanical properties, heat treatments, thermomechanically rolled, naval industry

1. Introduction

In time, the manufacturing technology of naval thick plates had to demonstrate its performance at the highest level throughout the technological flow, starting with the production of steel and continuing with casting, rolling and subsequent heat treatments which define the delivery condition in compliance with standards. At the same time, the assurance of constancy in manufacturing required the correlation of factors regarding the chemical composition, structure and use characteristics. The fulfilment of this requirement was possible by the development of new steel brands and the application of modern metallurgical processing technologies and procedures. The steel sheet for the shipbuilding industry can be delivered according to the ship's standards and regulations [1-8] in the state/condition of: rolled by heat treatment of normalization, thermal quenching / recovery, or thermomechanical treatment. Researches on the processing methods have demonstrated the effectiveness but also the diversity of thermal and thermo-mechanical treatment technologies for the production of flat rolled products with the most varied requirements in the field of shipbuilding [9, 10]. The transition from classical thermal treatments to thermo-mechanical treatments presents a number of advantages, of which important are those concerning the elimination of certain operations in the manufacturing technology and the reduction of energy and material consumptions. Among the thermomechanical processing technologies with applicability on an industrial scale, controlled rolling has been imposed.

The rolling/ lamination regime combined with controlled cooling or direct hardening from lamination represented the first studies in the field of thermomechanical treatments performed in order to establish a way to control the microstructure in the hot rolling process.

The introduction of special accelerated-cooling equipment systems has allowed the thermo-mechanical treatment technologies to be diversified through the development of increasingly complex combinations such as normalized rolling/lamination- the final deformation takes place within a temperature range resulting in a material with a structural condition equivalent to that obtained after normalization- or thermo-mechanical rolling where the final deformation takes place within a temperature range resulting in a structural condition and mechanical characteristics which cannot be achieved or kept by heat treatments only. Regardless of the processing mode though, it has been demonstrated that the obtaining of high mechanical characteristics is ensured only by the proper choice of the steel brand (chemical composition) and by strict compliance with the technological parameters specific to the metallurgical processing.

The beneficial effects of lowering the carbon content to improve weldability and microalloying with different elements should be exploited and combined with the benefits of an unconventional approach to the heat treatment process. Thus, in spite of the conservative positions to be found in the practice of thermal treatments, there are more and more research results that recommend incomplete austenitization for the normalization treatment of the naval plates or for the hardening of structural steels and the heat-affected zone in the welded joints, with some Ni- Mo or Ni-Mo-V low carbon steels [9-11]; by reducing the heat treatment temperature, the products of such steels have achieved increased values of both resistance and plasticity indices.

In USA for instance, use is made of biphasic alloys with Mn, V, Al with inter-critical thermal treatment, while in Russia, complex inter-critical controlled lamination tests were performed on metal structural steels and the results show values of strength ($R_{p0,2}$ > 500; R_m > 600 MPa) associated with values of extremely high plasticity properties and with a level of ductility almost twice as high as with normalized steel [9].

Deepening and systematizing the results of researches in this field is also the objective pursued in the development of experimental research, the results of which are partially presented in this paperwork.

Laboratory experiments will be able to draw a new orientation in the practice of heat treatments applied to naval steel products resulting in the development of technologically and economically optimal technologies.

2. Materials and experimental conditions

The experimental researches were carried out in the Micropilot Plant Laboratories and the Laboratory of Thermal Treatments and Surface Engineering of the Faculty of Engineering at “Dunarea de Jos” University of Galati. Samples of A36, D36 and E36 steel grades are taken from plates of 12,5; 15,5 and 30mm thickness which come from different batches of slabs manufactured at the A.M. Steel Works of Galati.

Table 1 shows the chemical composition of naval steels and Table 2 presents the mechanical properties of the naval plate steels in compliance with the naval standards.

Table 1. *The chemical composition of high-strength steel for the ship hulls as per standards [1, 2]*

	A32	D32	E32	**A36**	**D36**	**E36**	A40	D40	E40
Elements%	Calmed and fine grain steel						Calmed and fine grain steel		
Steel production conditions deoxidation	Calm steel and manufactured with fine grain								
Delivery State	According to Table 3								
C_{max}	0.18						0.18		
Mn	0.90–1.16						0.90–1.60		
Si, max	0.50						0.50		
P, max	0.040						0.04		
Cu, max	0.35						0.35		
Co, max	0.20						0.20		
Ni, max	0.40						0.40		
Mo, max	0.08						0.08		
Al_{sol}, min	0.015						0.015		
Mo	0.02–0.05						0.02–0.05		
V	0.05–0.10						0.05–0.10		
Ti, max	0.02						0.02		

Table 2. *Mechanical characteristics of high-strength steel for the ship hulls as per standards [1, 2]*

Steel grade	**Breaking Strength Rm**	**Yielding point Rc**	**Breaking Elongation *A5 (L_0=5.65S_0)**	**Impact bending test on Charpy specimens with V-notched longitudinal (L) and transverse (T) Breaking Energy (J) min**					
A36 **D36** **E36**	[N/mm^2]	[N/mm^2] min	[%] min	KV_L t ≤ 50 mm	KV_T t ≤ 50 mm	KV_L 50 < t ≤ 70 m	KV_T 50 < t ≤70 mm	KV_L 70 < t ≤ 100 mm	KV_T 70 < t ≤ 100 mm
	490-630	**355**	**21**	**34**	**24**	**41**	**27**	**50**	**34**

**) For tensile tests on flat specimens of thickness (t) equal to that of the plate, of 25 mm width and 200 mm calibrated length, the breaking elongation should correspond to the minimum values given in Table 2 bis*

Table 2 bis. *Minimum values for breaking elongation* ***A5*** *[2]*

Thickness t, (mm)	≤5	>5≥10	>10≤15	>15≤20	>20≤25	>25≤30	>30≤40	>40≤50
Breaking elongation %	**13**	**15**	**16**	**17**	**18**	**19**	**20**	**21**

Remark:

To ensure that every single class of steel has a single strain value regardless of the product thickness, a rule specific to shipbuilding design - it is necessary to compensate by appropriate technological solutions the metallurgical effects resulting from the change of the cooling rates after rolling or heat treatment depending on the thickness of the product.

Since the chemical composition is the main factor of influence on the material characteristics to ensure a satisfactory level of weldability, naval regulations prescribe for each grade of steel the maximum allowed values for carbon and manganese contents and the calculation of the equivalent carbon, leaving the manufacturer's freedom to regulate the chemical composition of the steel within these limits, depending on the product thickness. In order to execute the highly–stressed welded joints as required in the marine drilling platforms, the competent authority in the field such as the Romanian Naval Register (RNR) has introduced a new quality of products with guarantees of plasticity characteristics in the thickness direction as presented in Table 3 [3], and the state of delivery of the steels is mentioned in the quality certificate; certain categories of steels may be delivered in a rolled condition provided that satisfactory results are consistently obtained with shock bending tests.

Replacement of the normalization of the laminate semi-finished product with controlled temperature lamination or thermomechanical processing is acceptable only with the consent of the competent naval authority.

The chemical composition of the plates from which the samples were extracted is shown in Table 4, as compared to the product standard indications. They are steels additionally deoxidized with aluminium and of fine granulation, grading score 10.

Table 3*. Delivery state of the highly resistant steels [1, 2]*

Category	**Elements of granulation finishing**	**Thickness t (mm)**	**Delivery state/condition**
A32; **A36**; A40	Nb,V	≤12.5 >12.5	No (N), CR, or TM is regulated
A32; **A36;** A40	Al or Al+Ti	20<t≤35 >35	No (N), CR, or TM is regulated
D32; **D36;** D40	Nb,V	≤12.5 >12.5	No (N), CR, or TM is regulated
D32; **D36;** D40	Al or Al+Ti	20< t ≤25	No (N), CR, or TM is regulated
E32; **E36;** E40	Any	All	N, TM, (QT)

Table 4. *The chemical composition of the plates from which the samples were extracted*

batch	**Chemical elements [%]**													
	Steel	**C**	**Si**	**P**	**S**	**Al**	**Cu**	**Cr**	**Ni**	**Mo**	**Ti**	**Mn**	**V**	**Nb**	**B**
S1	**A36-1**	0.169	0.197	0.015	0.005	0.041	0.014	0.035	0.013	0.002	0.001	1.550	0.003	0.003	0.0002
S2	**A36-2**	0.169	0.212	0.020	0.006	0.045	0.013	0.032	0.076	0.001	0.002	1.528	0.006	0.002	0.0003
S1	**E36-1**	0.168	0.240	0.014	0.005	0.040	0.016	0.027	0.025	0.002	0.014	1.420	0.001	0.030	-
S2	**E36-2**	0.149	0.270	0.015	0.008	0.049	0.016	0.035	0.026	0.003	0.017	1.390	0.001	0.030	-

Analysing the chemical composition of the experimental batches, the following observations can be made:

- the carbon content of the batch varies within the range of 0.15-0.17 and is within the limits prescribed by the standard (max. 0.18);
- the silicon content ranges from 0.20-0.27 to 0.10-0.50 as prescribed in the norm and is estimated to be relatively constant in the batch concerned;
- the manganese content is within the range of: 1.39-1.55 and is within the limits prescribed by the standard (0.90-1.60);
- the aluminium content complies with the minimum allowed content and is approximately constant in the experimental batch composition, at around 0.40%;
- the same observations are also valid for the copper element;
- the chromium content in the range of 0.27 – 0.35% exceeds the maximum prescribed limit (0.20%) for all experimental batches;
- the nickel content is lower than that prescribed by the norm (0.20-0.40) for the two experimental batches of A36 quality;
- the molybdenum content comlies with the prescribed content (does not exceed 0.08% for any of the four batches);
- the content of titanium which is not regulated in the norm increases significantly with the E36 grade compared to A36 one;
- the vanadium content of the batch is significantly lower (0.001-0.006) than the prescribed one (0.05-0.10);
- the content of niobium increases significantly in E36 grade batches (0.03) being within the norm requirements (0.02-0.05) vs. A36 where the values are below the prescribed standard (0.002-0.003).

Boron is only found in the composition of A36 steel grade at very low values (thousandths of a percent).

In conclusion, it can be appreciated that for, the experimental batches, there are compositional deviations from the prescriptions of the naval norm. With some chemical elements such as nickel, niobium (values below those specified), chromium (values over the maximum normed content for all experimental batches), vanadium (values significantly lower than the prescribed ones). On the other hand, it can be seen that the effect of decreasing titanium and niobium content in the A36 batches compared to E36 ones may be counteracted by the presence of boron.

The samples were subjected to thermic and thermomechanical regimes using the existing aggregates and machines in the laboratories of the Faculty of Engineering (electric furnaces, mini rolling mills, hardness meters, metallographic sample preparation machine, metallographic microscope). The experimental regimes of thermal and thermomechanical processing on laboratory scale include the following variants:

I. regimes 2, 3, 4: complete austenitization* (supercritical heating at 880 °C) followed by cooling in different environments (air, oven, oil); II. regimes 5-10: complete austenitization (supercritical heating) followed by plastic deformation (10%, 30%, 40%) and cooling in different environments (air, water); III. regimes 11, 12: incomplete austenitization* (intercritical heating) followed by plastic deformation with a degree of deformation of 30% and air cooling.

Fig. 1. *Electric furnace used in experimental regimes of thermal processing on laboratory scale*

3. Experimental results and discussion

In Table 5 the experimental regimes are described by the characteristic technological parameters. After the application of the processing regimes, standard specimens have been made which have been put to a tensile/traction test under the terms of the hip plates specific rules.

The values obtained for the s mechanical properties of resistance (Rm, $R_{p0,2}$), plasticity (A5) and tenacity (energy absorbed, KV, determined on V- crest specimens) of the experimentally processed samples in the variants described above were compared with those obtained on the samples in the structural state provided by the classic rolling at different rolling end temperatures ($t_{e.r.}$).

Table 5. *Heat processing regime*

Nr Crt	**Regime**	**Heating temperature t [ºC]**	**Degree of plastic deformation ε [%]**	**Cooling media**
0	Rolled $T^{**}_{e.r.}$=850 ºC	-	-	-
1	Rolled $T^{**}_{e.r}$ =810 ºC	-	-	-
2	**C**	880 ºC	-	furnace
3	**D**		-	air
4	**E**		-	oil
5	**F**		10%	air
6	**G**		30%	
7	**H**		40%	
8	**I**		10%	water
9	**J**		30%	
10	**K**		40%	
11	**L**	880 ºC/760 ºC+ deformation	30%	water
12	**M**	760 ºC + plastic deformation		

(*) Critical batch points from which samples were experimentally processed were calculated and the results are: A_{C1}= 709 ºC; A_{C3}= 813 ºC
(**) end rolling temperature

Figures 2-5 presents the values of the mechanical properties of resistance (Rm, Rc), plasticity (A5) and tenacity (energy absorbed, KV) of the experimentally processed samples.

The results obtained under variant I, regimes 2, 3 and 4 confirm that the cooling medium, which determines an optimal set of physical-mechanical properties of strength and plasticity is the air. Very slow cooling (30-50 ºC/h) compromises the mechanical properties of resistance (e.g. the limit admissible value for mechanical tensile strength and values below the permissible limit of yielding/flowing), while rapid cooling in *oil* leads to very low values of the breaking elongation (values far below the prescribed ones.

This conclusion was used in the variants II and III, in the high temperature thermo-mechanical treatment regimes (with supercritical heating) and intercritical thermomechanical treatments (with heating in the intercritical range of the steels studied).

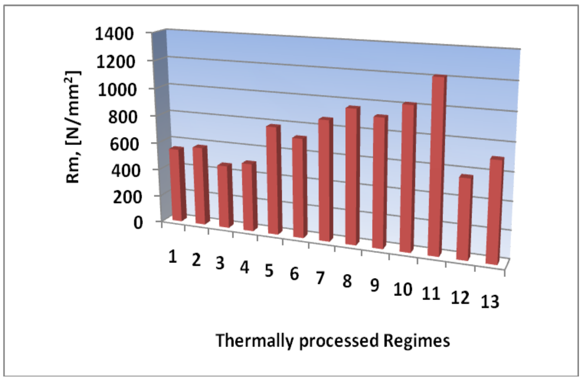

Fig. 2*. Variation of mechanical resistance values at breaking according to experimental processing regimes*

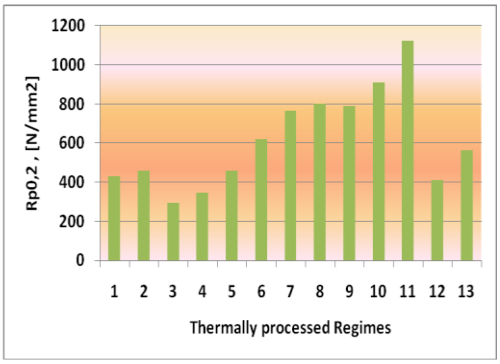

Fig. 3. *Variation of the yield point ($R_{p0,2}$) values according to experimental processing regimes*

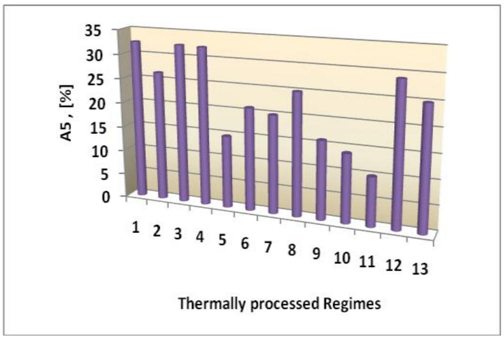

Fig. 4. *Variation of the elongation at break (A_5) values, according to the experimental processing regime*

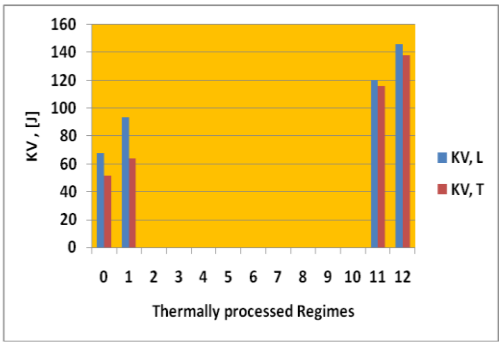

Fig. 5. *Variation of the of the energy absorbed (KV) values according to the experimental processing regime*

4. Microstructural aspects

Figures 6-10 show some microstructural aspects of thermally and thermomechanically processed samples in different variants and experimental regimes (A36 –S1-2).

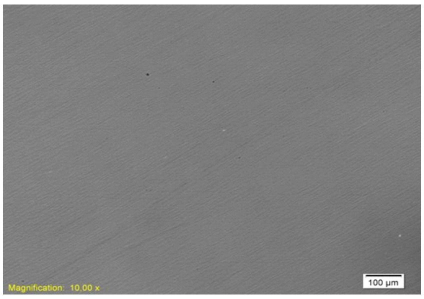

Fig. 6. *Purity of scoring material max.0,5 (laminated state, X100)*

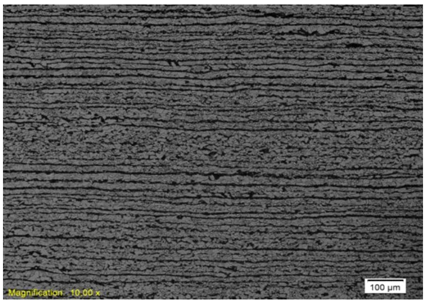

Fig. 7. *Ferrite-perlite structure in score ranges-strings 4-5; Grade size 9.5 (nital attack 3% X100)*

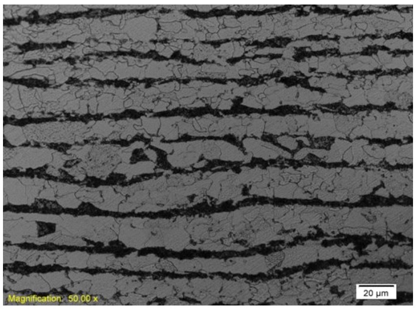

Fig. 8. *Perlite distributed in strings and oriented in the direction of deformation (nital attack 3% X500)*

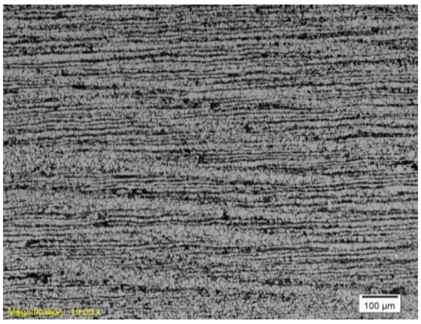

Fig. 9. *Thermally processed samples (variant I, regime1), X100*

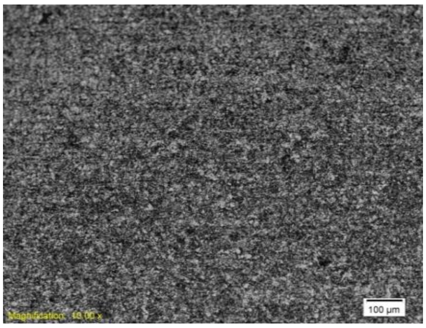

Fig. 10. *Thermally processed samples (variant I, regime 3), X100*

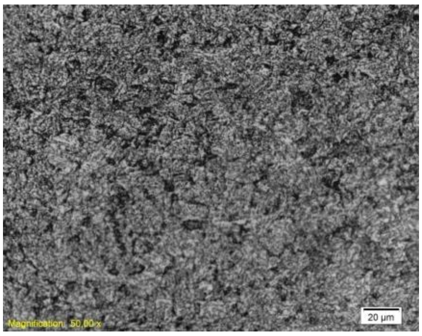

Fig. 11. *Thermomechanically processed samples according to regime 5*

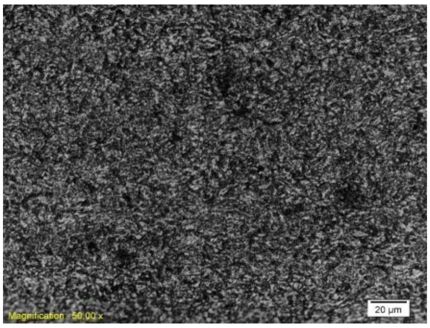

Fig.12. *Thermomechanically processed samples according to regime 6*

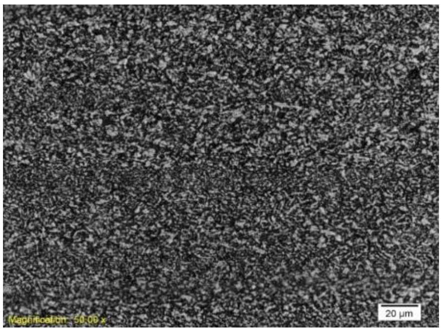

Fig. 13. *Thermomechanically processed samples according to regime 7*

5. Conclusions

The paper presents some results obtained in the study of the influence of thermal treatments, experimental variants applied in order to establish the optimal technological parameters (e.g. heating temperature, cooling medium) of the highly resistant naval steel. The objective of the research is to design the technology of thermal or thermomechanical processing of naval steels with a certain chemical composition under conditions of technical, technological and economic efficiency.

Preliminary results show that physical-mechanical characteristics can be obtained within the limits prescribed by the delivery rules of the heat-treated naval steels with minimal costs, provided the technology (technological parameters) correlated with the quality of the steel (the chemical composition) are known and rigorously complied with.

Modification of the mechanical properties correlated with the chemical composition and the structural state conferred by the type or method of metallurgical processing (rolling, conventional heat treatment or thermomechanical treatment) leads to the following conclusions with significant relevance in naval steel manufacturing with characteristics rigorously prescribed by the naval rules.

1. The decrease of the end-of-roll temperature causes the mechanical properties of resistance (Rm, $Rp_{0,2}$) to increase, while the plasticity (A5) and tenacity (KV) decrease.

2. The optimal cooling environment after rolling and after thermal and thermo-mechanical treatment is the air considering that:

2.1. Very slow cooling leads to structures with low mechanical properties, mainly affecting the yielding point ($Rp_{0,2}$ / see regime 2) whose values are below the allowable value for these steels (min.355 N/mm^2).

2.2. Accelerated cooling performed in environments such as oil or water has resulted in a decreased in plasticity, expressed by breaking elongation (see regimes 4, 8, 9, 10), and whose values are significantly lower than the admissible ones in all experimental thermal and thermomechanical variants prescribed by the norm (min. 21).

3. Thermomechanical treatments in the austenitic and plastic deformation experimental variants with 10%, 30% and 40% deformation rates, respectively, generally result in increased mechanical resistance with the increase of the degree of deformation both during final air cooling and final water cooling. It is noted, however, that the plasticity properties do not follow the same linear evolution as the degree of deformation.

4. It is highlighted the variant of thermomechanical treatment that requires complete austenitization with plastic deformation at higher deformation degrees (40% / see variant 7) and air cooling.

5. In spite of the very high values of the mechanical properties achieved by the austenitic thermo-mechanical treatment, accelerated cooling after plastic deformation irrespective of the degree of deformation compromises plasticity and tenacity of the material (see variants 8, 9, 10).

6. Good results were obtained from the thermo-mechanical treatment in incomplete austenitizing variants, particularly the direct heating in the inter-critical range of steel, the degree of plastic deformation of 30% and air cooling.

Following the above observations, we recommend for the A36, D36 and E36 naval steel plates low-temperature heat treatment technology with beneficial technical and technological effects.

Obtaining a set of mechanical (strength, plasticity and tenacity) characteristics in accordance with the naval register standards is possible under economical rolling and/or thermo-mechanical treatment conditions.

References

[1]. Rusanescu C. O., Jinescu C., Paraschiv G., Biris S., Rusanescu M., Ghermec O., *Influence of the Nb, V and Mo Elements on the Ecological Micro-alloyed Steel Properties,* Rev. Chim. (Bucharest), 66, No. 5/2015.

[2]. ***, STAS 8324-86, *Table pentru constructii navale.*

[3]. ***, *LR Rules July 2016 - for the Manufacture Testing and Certification of Materials*.

[4]. ***, *Registrul Naval Român - Reguli pentru clasificarea şi construcţia navelor maritime*, 1995.

[5]. ***, *STAS 9021/1-89 – Table de otel cu limita de curgere ridicata.*

[6]. ***, *SR EN 10113/2-1995 – Produse plate laminate la cald din oteluri de constructie sudabile cu granulatie fina*.

[7]. ***, *Det Norske Veritas*, 1993.

[8]. ***, *Lloyd's Register of Shipping*, 1995.

[9]. Popescu N., Constantin Ghe., Popescu O., *Tratamente termice neconventionale*, Editura Tehnică Bucureşti, p. 118-123 1990.

[10]. Levcovici T. D., *Contract nr. 748C/B29. Cercetări pentru promovarea tratamentelor intercritice la fabricaţia tablelor navale de înaltă rezistenţă*.

[11]. Iordache D. M., Nitu E. L., Plaiasu A. G., Botila L. N., Ducu M. C., Pasare M., *Analysis of Microstructure and Mechanical Properties of FSW Overlay Joints for Dissimilar Materials*, Rev. Chim. (Bucharest) 68, no. 8, 2004.