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Pilot production development of plate, steel grade EH36 applying thermo-mechanical controlled process at the rolling mill 3600

O.H. Kurpe[1*], V.V. Kukhar[2]

[1]*Metinvest holding, LLC, Mariupol, Ukraine,*
[2]*Department, Pryazovskyi State Technical University, Mariupol, Ukraine*
[*]*E-mail: aleksandr.kurpe@gmail.com*

Abstract

For the first time, technology has been developed, and experimental batch of shipbuilding steel plates (Grade EH36, 25 × 2150 × 8000 mm) has been produced according to the requirements of classification societies (Bureau Veritas Rules), at the rolling mill 3600, PJSC "AZOVSTAL IRON & STEEL WORKS". The technology is developed using general requirements for the manufacture of rolled products with the thermo-mechanical controlled process and mathematical model of the rolling process, on the basis of which the calculations of deformation schedules have been performed. The technical possibility of shipbuilding steel plates (Grade EH36, 25 × 2150 × 8000 mm) producing using thermo-mechanical controlled process (TMCP) instead of heat treatment accessing by normalization in accordance with Bureau Veritas Rules has been conformed at the rolling mill 3600. Introduction of the thermo-mechanical controlled process instead of normalization will reduce the production cost of the rolled products by eliminating natural gas consumption for heat treatment (normalization). To prepare the certification, in accordance with Bureau Veritas Rules, it is necessary to conduct an additional series of investigations for the rolled products (Grade EH36) of different thicknesses.

Key words: thermo-mechanical controlled process, hot rolling plate, shipbuilding steel, rolling mill technology.

Introduction

Having a significant number of benefits, thermo-mechanical controlled process (TMCP) has become more widespread in the production of almost all types of rolled products. As a result, consumers have received products that meet up-to-date quality requirements, and producers have an additional opportunity to reduce their cost production thereby maintaining, and, in some cases, greatly improving their competitiveness.

Nowadays, an extensive list of international standards make it possible to produce similar products in various ways, whether it be conventional hot rolling, normalizing rolling, thermo-mechanical controlled process (TMCP), or with the use of heat treatment. However, struggle for production cost, competition and product quality requirements assign clear priorities for the production method. There is a separate list of special-purpose product mix, which is still produced with the use of heat treatment only.

Thus, it is very important to undertake a series of studies and master the production of rolled products using thermo-mechanical controlled process (TMCP) instead of other more cost-effective methods, if the relevant standard for the product so allows.

Review of recent studies and publications

The worldwide development and dissemination of thermo-mechanical controlled process (TMCP) technology began in the 1960s of the last century [1]. In our country, the technology started to be introduced from production of rolled plates 10 years later [2]. Since that time, TMCP technology has evolved and relevant equipment has undergone drastic changes [3 - 5]. Now, this production method is constantly developing and spreading to various rolled products.

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Today, TMCP allows producing plates and coils for the design, construction, and production of pressure vessels and pipelines, the study of which is described in a large number of papers prepared by the authors from different countries around the world [3 - 18].

TMCP was predominantly used to produce low carbon steel plates [13, 14]. However, TMCP study with the use of steels, which carbon content is up to 40 %, has become more popular recently [19]. The thorough study and introduction of steels with a carbon content of 0.06 % and below was further developed with in-depth research of hardening processes and obtaining additional properties [8, 10, 15, 20, 21]. The research on the effect of various cooling rates during TMCP on the structure and properties of the rolled products is of particular interest [11, 22] and demonstrates the effect of substantial increase in properties with acceleration in cooling rate.

If the equipment allows, state-of-the-art technology will enable the production of rolled products with a yield strength of up to 800 MPa and more, but new higher levels of properties create also new challenges that require further study [12, 15].

With the development of technology and in-depth study of its influence on new properties of the rolled products, forecasting of the technology implementation results through the simulation of the development of microstructure and mechanical properties proposed by the paper authors [6, 7] became more widespread.

The great list of scientific papers shows that TMCP technology mastering for further production requires conducting a number of studies to demonstrate the capabilities of technology, equipment and obtain appropriate quality in accordance with the requirements of standards and customers [23 - 29].

The development of thermo-mechanical controlled process technology to produce shipbuilding steel plates (Grade EH36, 25 × 2150 × 8000 mm) instead of heat treatment by normalization at the rolling mill 3600 is a relevant target to ensure manufacture of the rolled products in accordance with modern requirements and allow reducing production costs.

Problem definition

The paper objective is to develop the technology of high-strength shipbuilding steel plate production (Grade EH36, 25 × 2150 × 8000 mm) in strict compliance with Bureau Veritas Rules at the rolling mill 3600, PJSC "AZOVSTAL IRON & STEEL WORKS".

Statement of basic materials

The existing equipment of the rolling mill 3600 currently consists of five duplicate pusher-type reheating furnaces, which are able to heat the slabs with a thickness of 130 - 350 mm, width of 1100 - 1920 mm, length of 920 - 3420 mm, and weight of 1.8-16 tonnes; descaler with a pressure of 150 atm; universal roughing stand, which provides for maximum rolling force of 11 MN with the vertical rolls and 46 MN with the horizontal rolls; duplicate carriage to transfer the rolled products with a thickness of 50.8 mm and more to further heavy plate treatment area; finishing reversing stand with a maximum rolling force of 46 MN (roughing and finishing stands are equipped with built-in 150 atm descalers on both sides); SMS Demag accelerated controlled cooling unit, including a cooling section of 25600 mm, 24 top and 24 bottom collector headers for laminar cooling (cooling rate is 12 - 45 °C/s); SMS Demag 9-roller hot-plate leveling machine; transverse cutting machine.

Layout of the main equipment of the rolling mill 3600 is shown in Fig. 1.

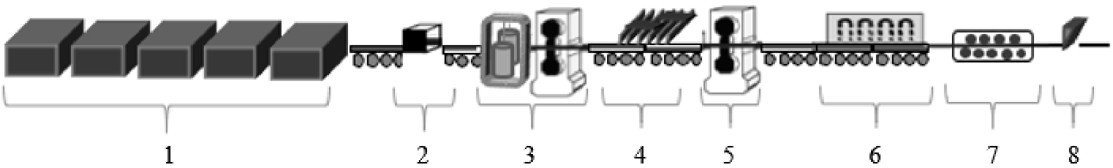

Fig. 1. Layout of the main equipment of the rolling mill 3600:
1 – reheating furnaces;
2 – descaler;
3 – universal roughing reversing stand;
4 – carriage for heavy plate transfer;
5 – finishing reversing stand;
6 – accelerated controlled cooling unit;
7 – roller hot-plate leveling machine;
8 – transverse cutting machine

The mill produces steel plates for structural, engineering, shipbuilding purposes, as well as for construction of the offshore drilling platforms, for the manufacture of large diameter high-pressure electric-welded pipes and other purposes. The rolled products have the following dimensions: thickness of 6-200 mm, width of 1500 - 3300 mm, length of 6000 - 24400 mm.

It should be noted that currently high-strength shipbuilding steel plates (Grade EH36) with a thickness of up to 50 mm are produced at the rolling mill 3600 using heat treatment – normalization, which is stated in the certificate No. 08458/D0 BV issued by Bureau Veritas.

According to Bureau Veritas Rules, steel plates (Grade EH36) with a thickness up to 100 mm can be produced with normalization or thermo-mechanical rolling process.

Following Bureau Veritas classification, NR 216 Rules, Chapter 2 (clause 1.7.3) [30], thermo-mechanical rolling, *TM* (thermo-mechanical controlled process, *TMCP*), provides for strict control of metal temperature and reduction during rolling. In general, we may observe larger percentage of the reduction at a temperature close to the temperature Ar_3, which can involve rolling in the two-phase region. The following normalization or other types of heat treatment cannot reproduce the post-TM (TMCP) properties. The accelerated controlled cooling (ACC) after rolling can be used by special approval of the company, which makes it possible to improve mechanical properties through the controlled cooling with a rate greater than ambient air cooling rate.

The slabs (220 × 1850 × 1590 - 1600 mm, 5.080 - 5.112 tonnes, heat No. 2104917) with the chemical composition given in Table 1 were used in experimental rolling.

The chemical composition of the experimental slabs fully meets the Rules on Materials and Welding for the Classification of Marine Units (NR 216), Chapter 2, established for the thermo-mechanical controlled process of rolled product manufacture (Grade EH36).

For comparison of chemical compositions, Table 1 demonstrates a typical chemical composition, which is currently used to produce the Grade EH36 with heat treatment – normalization. The chemical composition shown herein has a slight deviation from the composition used in the experimental rolling. However, excess of the prescribed carbon equivalent limit does not allow its use for the thermo-mechanical controlled process.

Table 1

Slab parameters for experimental rolling

Steel grade	Heat No.	CE	Chemical element content, %													
			C	Mn	Si	S	P	Nb	Cr	Ni**	Cu	V**	Ti**	Mo	Al	H
EH36	2104917	0.38	0.16	1.28	0.25	0.0040	0.019	0.033	0.03	0.03	0.03	0.003	0.012	0.005	0.04	4.9
EH36	typical*	0.37-0.41	0.14-0.16	1.32-1.35	0.22-0.26	0.005-0.011	0.009 - 0.018	0.032-0.038	0.03-0.08	0.02-0.13	0.02-0.05	-	-	-	0.028-0.040	3.1 - 4.7
BV Rules, NR 216, Chapter 2		≤ 0.38	≤ 0.18	0.90-1.60	≤ 0.50	≤ 0.035	≤ 0.035	0.02-0.05	≤ 0.20	≤ 0.40	≤ 0.35	0.05-0.10	≤ 0.02	≤ 0.08	≥ 0.015	-
		Amount of Nb + V + Ti ≤ 0.12%. Carbon equivalent (CE) is calculated according to the following formula: $CE = C + \frac{Mn}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$														

Notes: * typical chemical composition, which is used for the current production of the specified product mix with the use of heat treatment – normalization;** elements mentioned above are used separately or in combination.

When designing technology, there have been used the principles of controlled rolling at low temperatures, in particular, formation of the necessary structure and properties of rolled products when the deformation ends in the two-phase γ - α region. The plates (25 × 2150 mm, Grade EN36), which are currently produced with the normalization, have been taken as the experimental product mix.

The following target thermo-mechanical parameters of the rolling process have been calculated: deformation degree after receiving the rolled product width in the roughing stand of no less than 15 %; temperature conditions in the finishing stand; initial deformation temperature of 750 - 770 °C; final deformation temperature of 740 - 720 °C. The technology design has been based on the integrated mathematical model of the rolling mill 3600.

The target rolling pattern in the roughing stand is a transverse and longitudinal pattern with an increase in deformation, which provides on average constant rolling force of 23 MN between the passes. The thermo-mechanical controlled process has been introduced at the rolling mill 3600 in accordance with the developed temperature and deformation conditions (Tables 2, 3).

During the study, there have been used two patterns: longitudinal-transverse-longitudinal (breakdown with pulling) for batch No. 7052 and target-transverse-longitudinal for batch No. 7053.

Comparison of the calculation results with the actual rolling parameters is presented in Table 2 and 3.

The actual rolling parameters, including the deformation degree after the breakdown in the roughing stand, and the temperature conditions in the finishing stand were met.

The rolling force variation in the passes in the roughing and finishing stands is shown in Fig. 2 and 3.

Table 2

Target and actual parameters of plate production (25 × 2150 mm, Grade EH36) in the roughing stand at the mill 3600

Pass number	Target parameters				Actual parameters									
					batch No. 7052					batch No. 7053				
	thickness, mm	deformation degree, %	rolling force, MN × 100	temperature, °C	thickness (clock face), mm	thickness (recalculated)*, mm	deformation degree, %	rolling force, MN × 100	temperature, °C	thickness (clock face), mm	thickness (recalculated)*, mm	deformation degree, %	rolling force, MN × 100	temperature, °C
0	T221.7	-	-	-	221.7	-	-	-	-	T 221.7	-	-	-	-
1	190	14.3	2045.6	1150	200	202.2	9.6	2250	1128	180	182.7	21.3	2500	1125
2	154	18.9	2386.9	1146	180	182.3	10.9	2300	-	152	154.2	18.5	2250	-
3	T 131	14.9	2299.5	1142	145	147.7	23.4	2500	-	T 115	119.3	29.3	3420	-
4	110	16.0	2300.4	1136	K 123	127.4	15.9	3500	-	90	93.9	27.1	3200	-
5	91	17.3	2302.9	1129	100	103.9	22.6	3200	-	72	75.2	24.9	2820	-
6	75	17.6	2202.7	1121	T 72	76.1	36.5	3300	-	-	-	-	-	-

Notes: *T* – means turning; * actual thickness of the feed recalculated with due regard to the stand stiffness

Table 3

Target and actual parameters of plate production (25 × 2150 mm, Grade EH36) in the finishing stand at the mill 3600

Pass number	Target parameters				Actual parameters									
					batch No. 7052					batch No. 7053				
	thickness, mm	deformation degree, %	rolling force, MN × 100	temperature, °C	thickness (clock face), mm	thickness (recalculated)*, mm	deformation degree, %	rolling force, MN × 100	temperature, °C	thickness (clock face), mm	thickness (recalculated)*, mm	deformation degree, %	rolling force, MN × 100	temperature, °C
0	75					76.1					75.2			
1	71	5.3	2427.1	760	66	66.8	12.2	3450	768	65	65.6	12.8	3370	767
2	65	8.5	3419.2	756	56	58.2	12.9	4300		57	58.4	11.0	3820	
3	59.5	8.5	3322.9	754	48	50.3	13.6	4370		51	52.6	9.9	3950	
4	54	9.2	3452.6	752	42	44.2	12.1	4320		45	46.6	11.4	3950	
5	49	9.3	3345.3	750	38	39.1	11.5	3670		40	41.5	10.9	3900	
6	44	10.2	3501.9	747	34	35.1	10.2	3650		36	37.3	10.1	3750	
7	39.5	10.2	3393.9	744	31	31.6	10.0	3370		32	33.3	10.7	3770	
8	35	11.4	3570.2	741	29	29	8.2	3020		29	30	9.9	3570	
9	31	11.4	3458.9	737	29	26.6	8.3	1550	738	27	27.3	9.0	3200	
10	27.5	11.3	3274.6	736						26.5	25.6	6.2	2470	721
11	25	9.1	2654.1	734										

Notes: *T* means turning; * actual thickness of the feed recalculated with due regard to the stand stiffness

The rolling pattern in the roughing stand, which was used in the production of the batch No. 7053, is more appropriate, since it allows, with an increase in the deformation degree, reducing number of passes and, with an increase in rolling forces in the passes 3, 4 and 5, reducing rolling cycle. This pattern is closer to the target one.

The rolling pattern used in the production of the batch No. 7052, owing to the phase changes in the longitudinal (passes 1 - 3, 6) and transverse (passes 4 - 5) rolling, with due regard to the target pattern, resulted in the rolling force growth due to increase in the rolling product width in transverse passes.

When compared with the batch No. 7053, this pattern has an increased number of passes, therefore, it is longer-term and more energy-consuming.

After rolling and final cooling, samples were taken from the rolled products to conduct a series of mechanical tests (main and additional) in accordance with BV Rules, NR 216, Chapter 2, and BV Rules, NR 480 Approval of the Manufacturing Process of Metallic Materials. The test results are shown in Table 4 and Table 5.

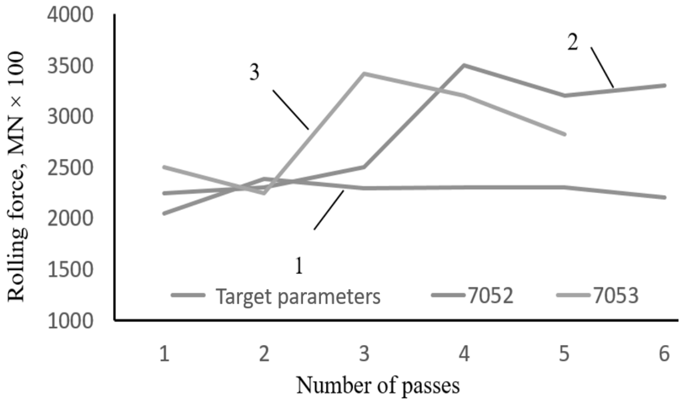

Fig. 2. Rolling force variation in the passes in the roughing stand when calculating target conditions (1) and actual rolling of the batches No. 7052 (2) and No. 7053 (3)

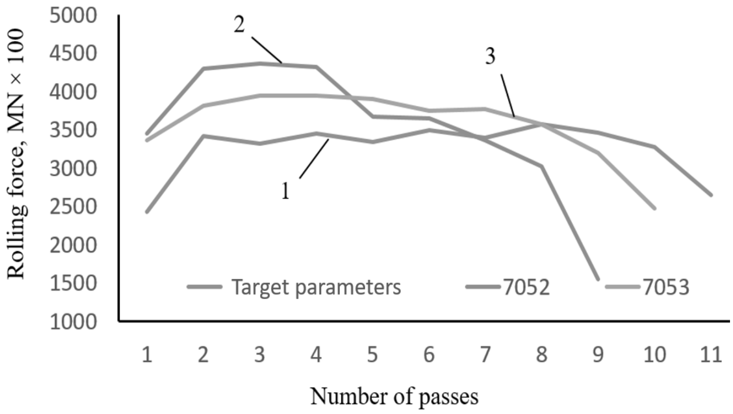

Fig. 3. Rolling force variation in the passes in the finishing stand when calculating target conditions (1) and actual rolling of the batches No. 7052 (2) and No. 7053 (3)

The rolling patterns used in the roughing stand are shown in Fig. 4. In general, the implemented scheme of the thermomechanical rolling process are shown in Fig. 5.

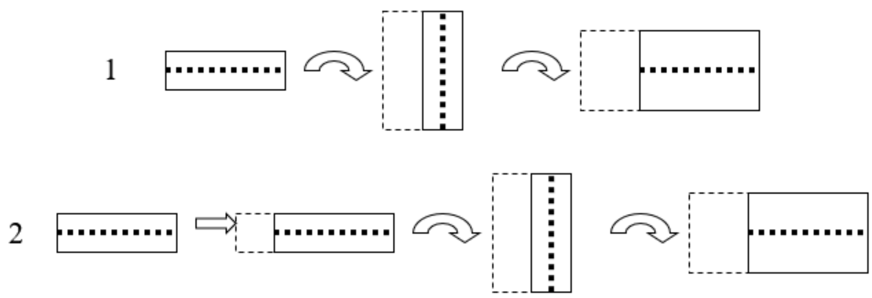

Fig. 4. Rolling pattern in the roughing stand, actually used in the batch No. 7053 (1) and actually used in the batch No.7052 (2)

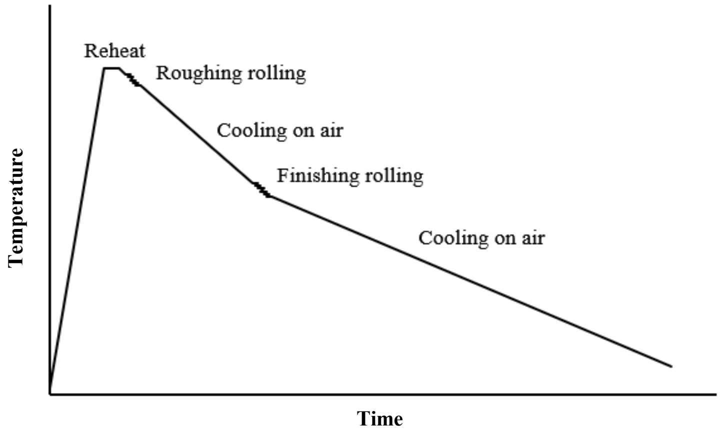

Fig. 5. The implemented scheme of the thermomechanical rolling process in general

Table 4

Main test results for the rolled products in accordance with BV Rules, NR 216, Chapter, and BV Rules, NR 480

Type of tests	BV requirements	Test results		Data compared with the post heat treatment and normalization condition
		batch No.7052	batch No.7053	
Rolled product thickness, mm		25	25	23-27
Yield strength, R_{eH}, MPa, min.	355	437	450	367-426
Tensile strength, R_m, MPa	490-630	550	560	496-540
Elongation, A_5, %, min.	21	30	30	25-36
Average impact energy, J				
KVL_{-40} (longitudinal test)	34	144/166/155	142/125/149	194/204
KVT_{-40} (transverse test)	24	99/105/107	116/107/117	

To compare the existing technology with the experimental rolling, Table 4 shows the test results for the rolled products manufactured with normalization and using TMCP technologies.

Table 5

Additional test results for the rolled products in accordance with BV Rules, NR 216, Chapter, and BV Rules, NR 480

Type of tests	Test results	
	batch No. 7052	batch No. 7053
1	*2*	*3*
Tensile test (with stress relief) at 600°C (2 min/mm), min. 1 hour		
Yield strength, R_{eH}, MPa, min.	435	459
Tensile strength, R_m, MPa	548	556
Elongation, A_5, %, min.	30	31
Impact test on the specimens without ageing, J		
KVL_0	171/192/187	149/177/182
KVL_{-20}	185/187/192	173/188/146
KVT_{-20}	143/135/132	132/142/136
KVL_{-40}	144/166/155	142/125/149
KVT_{-40}	99/105/107	116/107/117
KVL_{-60}	113/127/117	104/112/115
KVT_{-60}	80/72/81	77/96/86
Impact test on the specimens with deformation aging, J		
KVL_{-20}	158/153	184/166
KVL_{-40}	107/113	140/116

Table continuation 5

1	2	3
KVL_{-60}	48/10	70/84
$Fiber_{-60}$, %	40/0	90/100
Non-metallic inclusions (average / maximum rating)		
Brittle silicates CX, points	2.1/2.5	0.8/1.5
Undeformed silicates, CH, points	2.0/2.5	1.5/2.0
Sulfur prints	In the axial zone, there is sulfur accumulation in the form of spots and individual short irregular segregation lines	
Microstructural examination	Ferrite-pearlitic, with an increase in the perlite component fraction in the axial zone	
Size distribution	9; 10	9; 10
Through-thickness tensile testing, Z, %	61/67	60/52

Thus, the results of the main mechanical tests of rolled products manufactured according to thermo-mechanical rolling conditions, fully meet the requirements contained in BV Rules.

In general, additional tests also demonstrated positive results. The only exceptions were impact test results for the samples taken from the batch No. 7052 with deformation aging and assessment of the fiber share in the fracture at -60 °C, which showed a lower level of properties. These results require additional testing and a microstructure study.

Slight increase in the properties obtained during tensile tests of the batch No. 7053 can be attributed to the use of more intense rolling schedule in the roughing stand.

Thermo-mechanical rolling allowed obtaining a finer ferrite grain (10; 9 points) in comparison with normalization (8; 9 points) for the comparable product mix.

When comparing with the tensile strength test results on the comparable product mix manufactured with normalization, thermo-mechanical rolling provides a higher level of yield strength and tensile strength, so it could be said that it is possible to optimize the technology and chemical composition of steel.

Conclusions

1. The technical possibility of producing shipbuilding steel plate (Grade EH36) using thermo-mechanical controlled process (TMCP) at the rolling mill 3600, PJSC “AZOVSTAL IRON & STEEL WORKS”, has been confirmed.

2. For the first time, at the rolling mill 3600, PJSC “AZOVSTAL IRON & STEEL WORKS”, an experimental batch of the rolled products (Grade EH36) has been produced with TMCP in strict compliance with Bureau Veritas Rules, a complex of main and additional tests has been carried out, which demonstrates the possibility of further mastering of the technology and product certification.

3. Introduction of the thermo-mechanical controlled process instead of normalization will reduce the production cost of the rolled products by eliminating natural gas consumption for heat treatment (normalization).

4. To prepare the certification, in accordance with Bureau Veritas Rules, it is necessary to conduct an additional series of investigations for the rolled products (Grade EH36) of different thicknesses.

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Курпе О.Г., Кухар В.В. Дослідне освоєння виробництва товстолистового прокату з марки сталі ЕН36 із застосуванням термомеханічного контрольованого процесу на стані 3600

Вперше розроблена технологія, та виготовлена дослідна партія товстолистового прокату з судносталі підвищеної міцності марки ЕН36, розмірами 25×2150×8000 мм. Дослідна партія виготовлена відповідно до вимог класифікаційного товариства Бюро Верітас на прокатному стані 3600 ПАТ «МК «АЗОВСТАЛЬ». Технологія розроблена з використанням загальних вимог до виготовлення прокату з термомеханічного контрольованого процесу та з використанням математичної моделі процесу прокатки, на підставі якої виконано розрахунки режимів деформації. Підтверджена технічна можливість виготовлення товстолистового прокату з судносталі підвищеної міцності марки ЕН36 розмірами 25×2150×8000 мм з використанням термомеханічного контрольованого процесу (ТМСР) замість термічної обробки шляхом нормалізації, відповідно до правил Бюро Верітас на прокатному стані 3600. Застосування термомеханічного контрольованого процесу, замість нормалізації, дозволить знизити собівартість прокату за рахунок виключення споживання природного газу для термічної обробки (нормалізації). Для підготовки сертифікації, згідно Правил Бюро Верітас, необхідно провести додаткову серію досліджень для прокату марки ЕН36 у різних товщинах.

Ключові слова: термомеханічний контрольований процес, товстолистовий гарячий прокат, сталь для суднобудування, технологія прокатки