THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N°. 2 - 2016, ISSN 1453 – 083X

RESEARCH IN INDUSTRIAL TRIALS TO IMPROVE THROUGH-THICKNESS Z35 PROPERTIES OF HOT ROLLED HEAVY PLATES UP TO 60 MM THICKNESS FOR STRUCTURAL STEELS

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ABSTRACT

The main purpose of this industrial experimental rolling, done in ArcelorMittal Galati in the Heavy Plate Mill is to check the correlation between mechanical properties and the microstructure of chemical compositions used in trial in order to reach through-thickness Z properties. First chemical composition is C_Mn steel with mechanical properties designed to reach at least 275 MPa on yield strength. The other chemical composition is based on Nb and Ti alloying elements with mechanical properties designed to be equal or higher than 360 MPa. In total, four slabs with 250 mm thickness were rolled. Two slabs with targeted plates thickness of 22.5 mm and 60 mm were used in trial per each chemical composition in order to check the thickness feasibility of targeted through-thickness Z properties.

KEYWORDS: trough-thickness, Z25, Z35, structural steels, ship structures, offshore structures, beams in bridge constructions

1. Introduction

Z35 through-thickness mechanical properties is a specially processed steel grade, which takes into consideration the requirements of heavy steel construction. The possibility of lamellar tearing occurring in stiff welded joints has been prevented by improving the perpendicular properties of steel.

Definition of Z plates, quality classification and dimension range: the properties of the Z plates perpendicular to the plate surface are better than those properties of the corresponding grade of general structural steel. The letter Z refers particularly to the thickness in xyz-coordinates of the plate width x length x thickness. The through-thickness deformation properties are determined with the tensile test using test pieces that are machined in through-thickness direction of the plate. The result is the perpendicular reduction of area at fracture, that is, the so-called Z value. The Figure indicates the reduction of the cross-sectional area of the tensile test piece during the tensile test, i.e. perpendicular reduction of area in percentage. This calculated Z value sets a basis for the quality classification of Z plates, as shown in Table 1.

Table 1. *Z quality classes and the corresponding reduction of area values for Z plates according to EN 10164*

Z quality class	**Requirements for reduction of area value (Z values)**	
Quality class designation	**Minimum average value, requirement for three tests %**	**Minimum individual value requirement %**
Z15	15	10
Z25	25	15
Z35	35	25

For plates of thickness less than 15 mm the standard EN 10164 does not require through-thickness tensile tests and these tests are not carried out. However, the same manufacturing process is used for all the Z plates regardless of the thickness

For Z plates the standard ASTMA 770 also deals with the steel plates having improved through-thickness properties. In this standard, Z plates are defined as plates that have reduction of area value Z ≥ 20%. Z plates with improved through-thickness properties can be delivered within the thickness range of ≥ 25 mm. Z guarantees for thinner plates according to separate agreement. For other dimensions the corresponding dimension range of heavy plates is effective.

For steel grades, product shapes and properties Z plates can be ordered in any of the steel grades included in the heavy plate production programmed. Z plates are used in all parts of the world as structural steels, pressure equipment steels, ship construction steels and offshore steels. In addition to heavy plates, shop-primed plates and a wide selection of prefabricated plate products are also available. Prefabricated products that are ready for installation can be tailor-made, cut, bent and/or beveled in accordance with the customer's requirements. The chemical composition, mechanical properties as well as usability in the engineering shop are determined by the steel grade.

Z plates are manufactured and tested primarily according to the requirements set in the relevant steel standard or in the Rules of the classification society in question. During the manufacture of the steel, special additional treatment is used to improve the through-thickness properties of the finished plates. If the material standard does not specify requirements for Z plates and the purchaser does not indicate any specific requirements, the standard EN 10164 will be applied.

Regarding the occurrence of lamellar tearing in steel structures, the lamellar tearing as a failure type of steel structures is extremely uncommon and when it occurs, it usually takes the form of cracking parallel to the surface of the plate and in association with a welded joint. The cracks are on different planes and are connected to one another in a step-like form. Most sensitive to this are stiff, fillet and butt welded L and T joints, where large through-thickness stresses may occur. When assessing the possibility of occurrence of lamellar tearing, the empirical values for through-thickness reduction of area presented in Table 2 can be used. The industrial trials were done in ArcelorMittal Galati.

Table 2. *Values for reduction of area in the through-thickness direction*

Reduction of area in the through-thickness direction %	**Probability of occurrence of lamellar tearing**
Z ≥ 35	Extremely unlikely.
20 ≤ Z < 35	Extremely rare.
15 ≤ Z < 20	Possible in welded joints highly loaded in the through-thickness direction of the plate.
10 ≤ Z < 15	Possible in welded joints moderately loaded in the through-thickness direction of the plate.
Z < 10	Possible in welded joints only lightly loaded in the through-thickness direction of the plate.

2. Tracking and traceability of products followed in Z35 industrial trials

For the trial designation on drawing the heavy plates according with DNV rules of the steel grade A to EH36 with Z quality class reaching Z35 according to EN 10164 were designated with the following example: DNV rules + EN 10164-Z35.

Flow production process starts from SMS (SMS = steel melting shop) and CC (Continuous casting); HPM (heavy plate mill) hot rolling and normalizing and further heat treatment with laboratory tests for 4 plates with two thickness plates target, namely 22.5 mm and 60 mm, taken from 4 different heats scheduled, elaborated and casted, were rolled and normalized. In Table 3 are shown dimensional slabs used in trial.

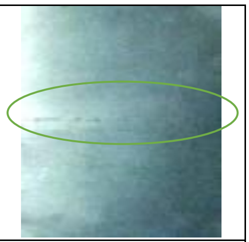
The first analysis concerned the macrostructure of slabs used in trial.

In Table 4 we have the Bauman prints for each slab. We can observe small center lines in the middle of the thickness.

Table 3. *Dimensions of slabs used in Z35 trial*

Trial no	**Slab thickness**	**Slab width**	**Slab length**	**Plate thickness**	**Slab width**	**Slab length**
1	250	1500	1999	22.5	3120	11000
2	250	1500	2035	22.5	3120	11000
3	250	1500	4040	60	3100	10000
4	250	1500	3570	60	3100	9000

Table 4. *Macrostructure analysis – Bauman print - central segregation and core defects – class 2*

			
Trial no. 1	Trial no. 2	Trial no. 3	Trial no. 4

3. Hot rolling

3.1. Processing conditions for trials

The delivery conditions of Z plates are defined in standards with N – normalizing heat treatment in furnace. Our purpose is to have the final rolling temperature in austenitic area above Ar_3, which means the rolling schedule will be in two phases. One phase will be in roughing area were the transfer bar thickness between two stands will increase s – roughing mill and finishing mill. In finishing mill, the transfer bar will be rolled in one phase with one cooling point. The cooling point will be 60 °C above Ar_3 in austenitic zone. We prepared 4 chemical compositions of steel grade equivalent with NVE and NVE36 according with DNV rules. Preliminary laboratory tests showed that the combination of austenitic rolling followed by normalizing heat treatment can increase the Z35 trough-thickness properties. The lab trials were focused on Z25 through-thickness properties of thick plates with a similar chemical composition used in the described trial as it can be seen in Table 5. Now the objective is to determine up to which degree of thickness such a lean chemistry composition could be used to reach Z35 properties. Purposed chemistry and the traceability of trial are described in Table 5.

Table 5. *The chemical composition used in trial*

No.	C	Mn	Si	P	S	Al	Ni	Cu	Cr	Ti	Mo	Nb	V	N
1	0.170	1.09	0.21	0.011	0.003	0.038	0.016	0.016	0.027	0.002	0.003	0.002	0.002	0.0051
2	0.172	1.45	0.22	0.012	0.005	0.034	0.014	0.019	0.025	0.009	0.003	0.036	0.028	0.0057
3	0.157	1.34	0.27	0.013	0.003	0.042	0.239	0.014	0.024	0.018	0.002	0.018	0.025	0.0054
4	0.180	1.31	0.27	0.010	0.004	0.038	0.240	0.017	0.022	0.019	0.003	0.037	0.055	0.0055

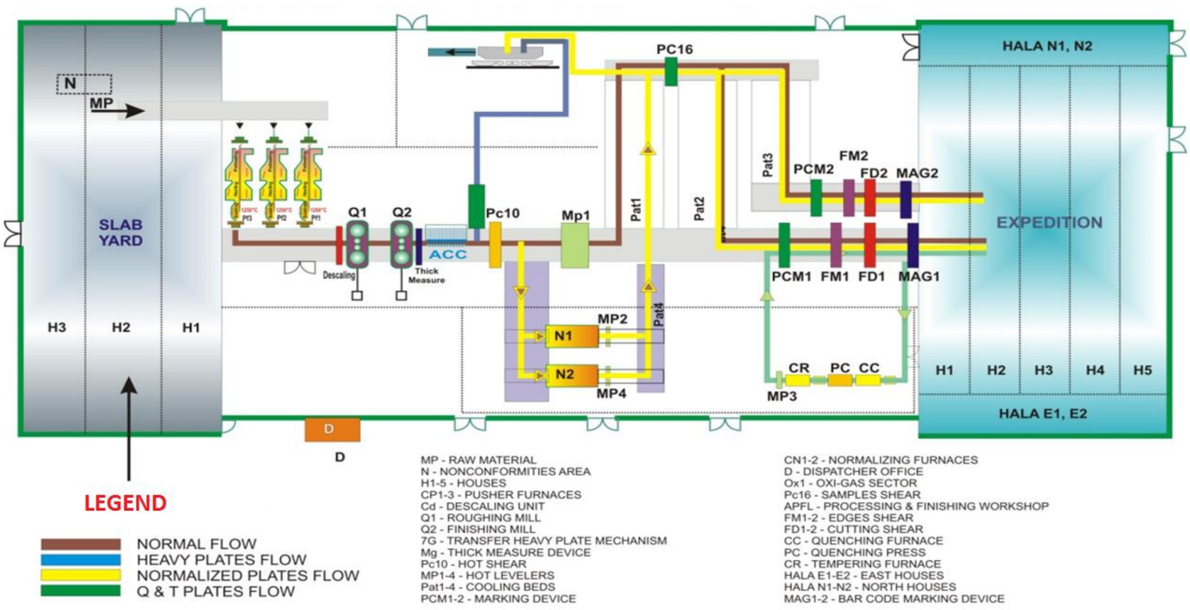


Fig. 1. *Heavy Plate Mill flow production process*

Table 6. *Pushing furnace data (reheating data)*

Trial no.	CP Line	Preheating time [hours]	Heating time [hours]	Soaking time [hours]	Average temperatures preheating zone [°C]	Average temperatures heating zone [°C]	Average temperatures soaking zone degrees [°C]	Discharging temperature [°C]
1	2	1:18	2:10	1:37	1065 / 1001	1269 / 1278	1259 / 1259	1187
2	1	1:17	2:00	1:36	1061 / 1060	1270 / 1281	1259 / 1259	1165
3	2	1:20	2:10	1:37	1061 / 1060	1269 / 1278	1252 / 1252	1160
4	1	1:22	2:00	1:31	1061 / 1060	1270 / 1281	1259 / 1259	1173

Specific time to reheating slabs of the steel grades equal to 1.5÷2 min/mm

Rolling data:

- Q1 roughing mill stand; reversible quarto mill stands; locked frame: Maximum dimensions on plates: thickness > 14 mm / width: 1500-4600 mm / maximum length: 16500 mm. Transfer bar thickness for Q2 = 30-120 mm.

- Q2 finishing mill stand; reversible quatro mill stands; open frame: Maximum dimensions on plates: thickness: 6 ÷ 150 mm / width: 1500÷4200 mm / maximum length: 50000 mm.

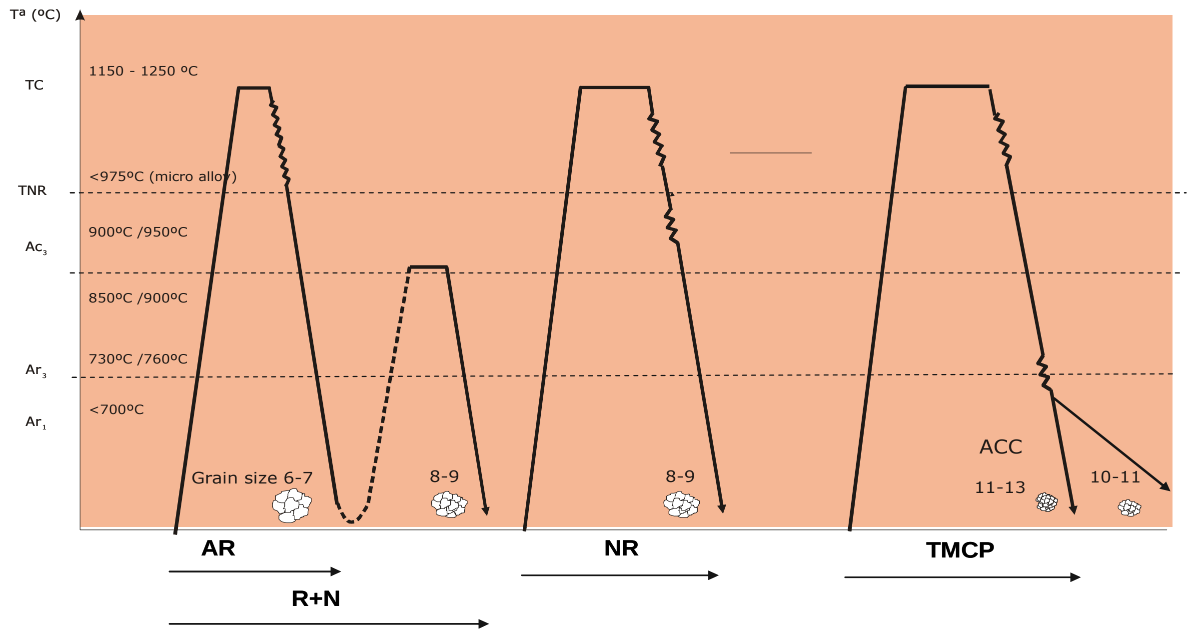


Fig. 2. *Type of rolling = R + N control rolling followed by normalizing heat treatment*

Table 7. *Rolling process data*

No.	Slab thick [mm]	Slab width [mm]	Slab length [mm]	Plate thick [mm]	Plate width [mm]	Plate length [mm]	Descaling pressure [bar]	Start rolling temperature in Q1 [°C]	Transfer bar thick. [mm]	Start rolling temperature in Q2 [°C]	End rolling temperature in Q2 [°C]	Total percentage reduction in Q2 [%]
1	250	1500	1999	22.5	3120	11000	170	1170	67	870	814	33.58
2	250	1500	2035	22.5	3120	11000	170	1150	67	870	815	33.58
3	250	1500	4040	60	3100	10000	170	1150	110	840	812	54.54
4	250	1500	3570	60	3100	9000	170	1170	110	840	816	54.54

About the control rolling process the discharging from the pushing furnace, followed by descaling at 170 bar pressure will be Q1 the entry temperature around 1150 ºC and the rolling strategy = pre-sizing sequence and the broad-sizing sequence from 2 turns; followed by realizing the transfer bar thickness; cooling time in oscillation are to achieve Q2 start temperature, rolling passes to achieve final thickness at the temperature aimed. The total percentage reduction in Q2 is equal or higher than 55%. Next step is normalizing heat treatment. All data are in the next table and the next figures will show rolling temperatures function of thickness, and exit thickness function of rolling passes.

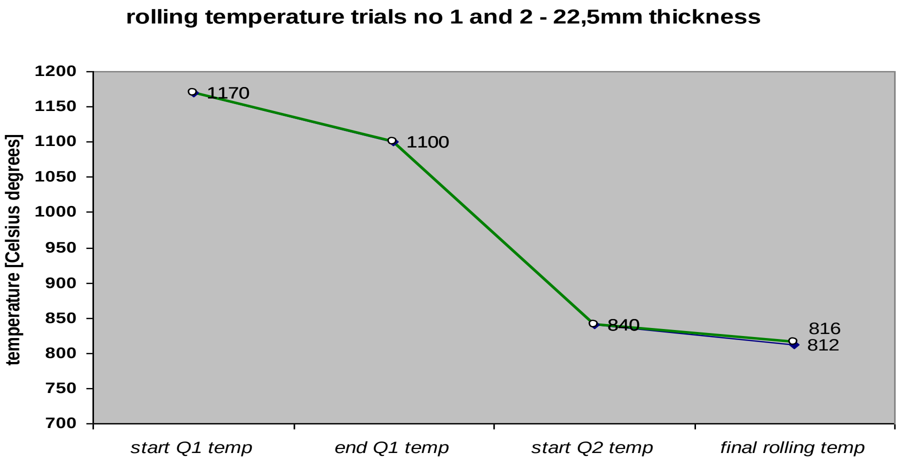


Fig. 3. *Rolling temperature for plates with 22.5 mm final thickness*

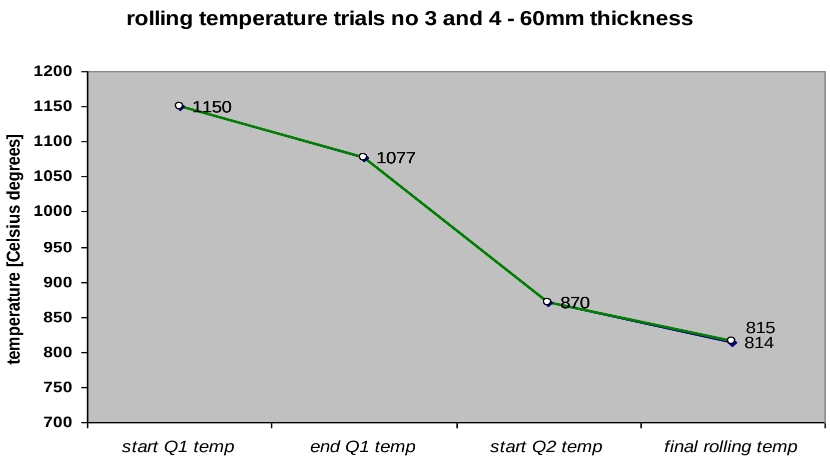


Fig. 4. *Rolling temperature for plates with 60 mm final thickness*

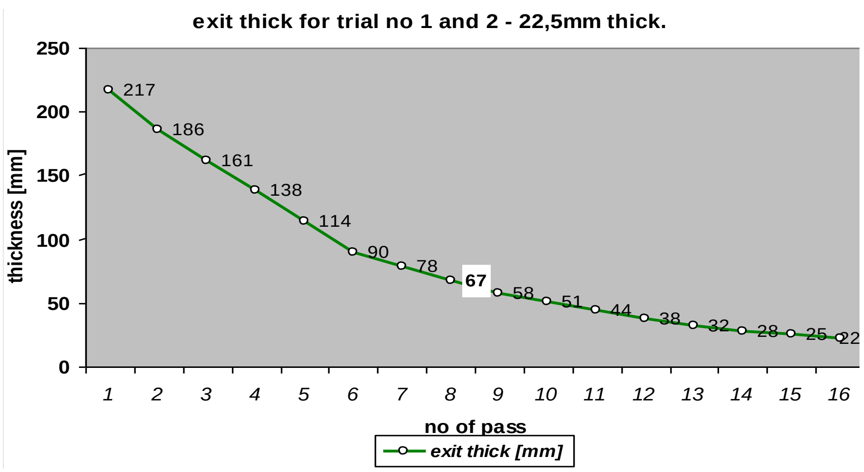


Fig. 5. *Exit thickness at rolling pass for plates with 22.5 mm thickness*

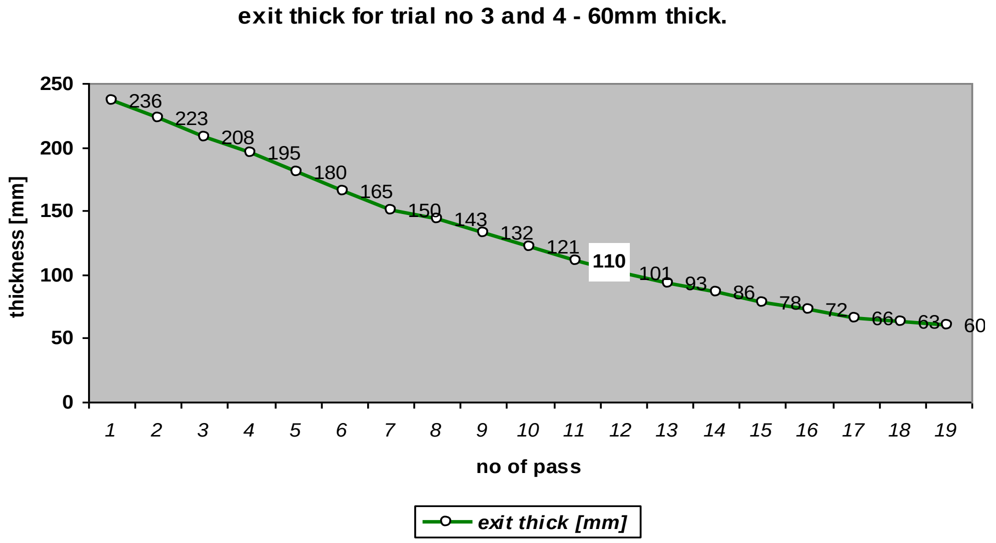


Fig. 6. Exit thickness at rolling pass for plates with 60 mm thickness

3.2. Normalizing data

Normalizing N metallurgical route is a separate heat treatment after rolling involving austenitising (above the transformation range Ac_3). Normalizing relieves the internal stresses caused by previous working, and while it produces sufficient softness and ductility for many purposes, it leaves the steel harder and with a higher tensile strength.

Table 8. *Normalizing furnace data*

No.	Slab thick. [mm]	Slab width [mm]	Slab length [mm]	Plate thick. [mm]	Slab width [mm]	Slab length [mm]	Temperature set on burners zone 1-12 [°C]	Total time spent in furnace [minutes]
1	250	1500	1999	**22.5**	3120	11000	**880**	**49**
2	250	1500	2035	**22.5**	3120	11000	**880**	**50**
3	250	1500	4040	**60**	3100	10000	**880**	**101**
4	250	1500	3570	**60**	3100	9000	**880**	**120**

Specific time to normalize plates depends of the thickness range and steel grades between 1.6÷2.2 min/mm

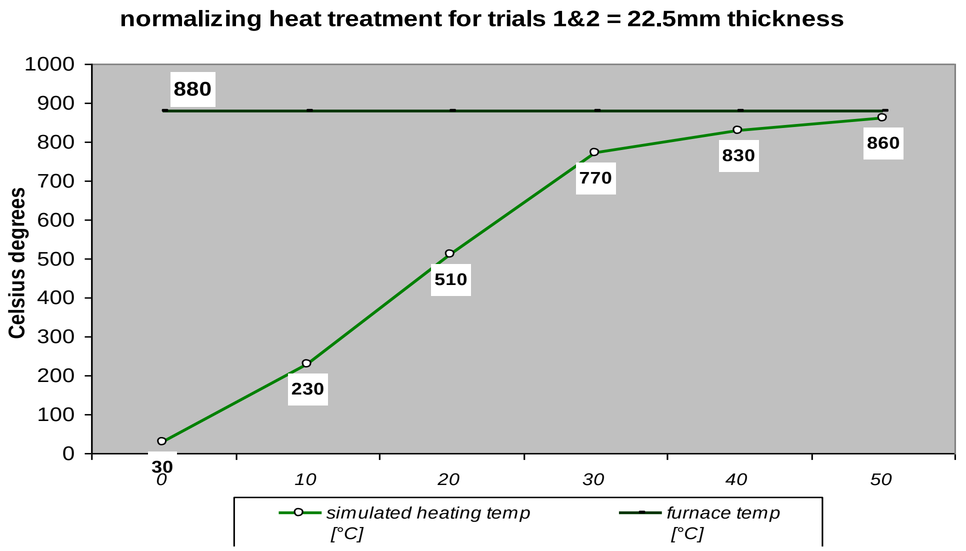


Fig. 7. Normalizing plate temperature plate with 22.5 mm thickness

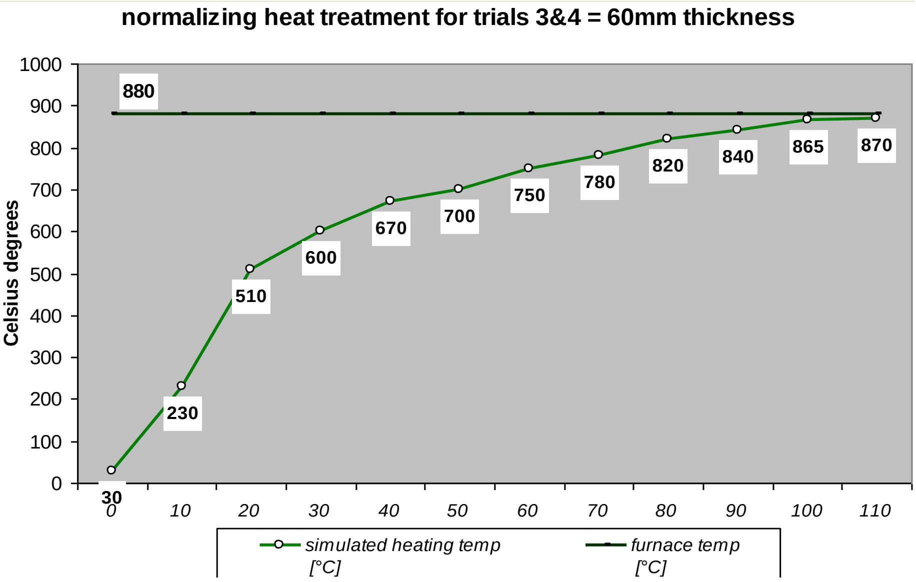


Fig. 8. *normalizing plate temperature - plates with 60 mm thickness*

3.3. Material testing and sampling

Z plates are manufactured and tested primarily according to the requirements set in the relevant material standard or in the rules of Classification Society in question. If the standard does not specify requirements for Z plates and the purchaser does not indicate any specific requirements, standard EN 10164 will be applied. A test unit and the sampling are defined in EN 10164. The through-thickness tensile test and the calculation of the through-thickness reduction of area are defined in the standard EN 10002-1. The test result assessment is based on the sequential method defined in the standard EN 10021.

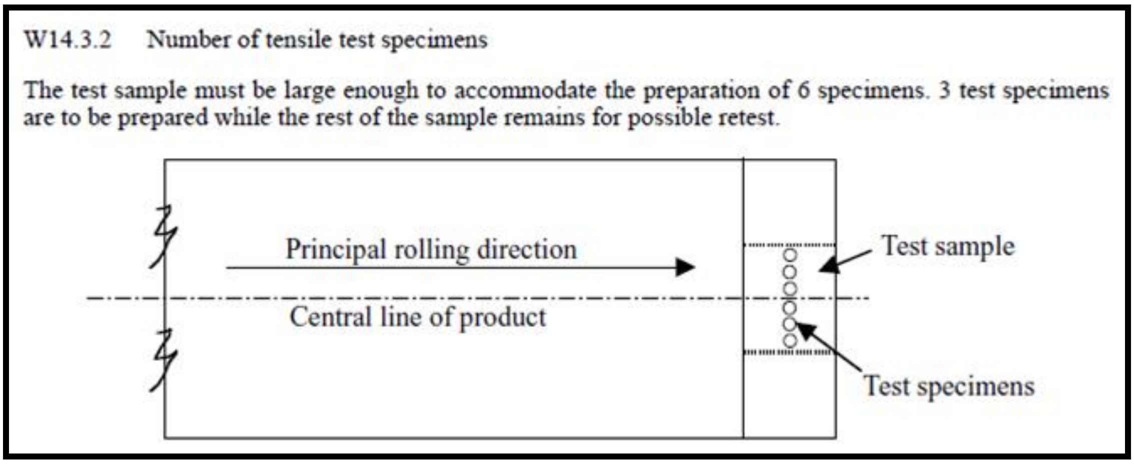


Fig. 9. *Test sample according to EN 10002-1*

Ultrasonic test performed S1E1 conf. EN10160:2009: the testing of Z plates always includes ultrasonic testing which is carried out according to the requirements of EN 10160 class S1. It must be noted that the normal ultrasonic technique cannot be used for determining resistance to lamellar tearing. UT test was performed with Olympus Flaw detector, model EPOCH600: probe diameter φ = 21 mm, test frequency = 4 MHz, scanning area between 100-200mm. The results are shown below.

Mechanical tests performed on INSTRON testing machine are listed below.

- One tensile test for each sample in transverse direction according to DNV Rules for classification of Ships / High Speed, Light Craft and Naval Surface Craft, Section 1, chapters B and C / 2011;

- One Charpy test notch in transverse direction KV at -40 °C (negative Celsius degrees) for each sample transverse test according to DNV rules / 2011;
- Z35: 2 tests with 3 samples according with EN 10164/2004;
- Table 10 presents data of INSTRON testing machine presets for tensile test;
- Table 11 presents results of the mechanical properties of plates rolled.

In Figure 10 we can observe very good toughness properties with an average of 100 Joules for 22.5 mm thickness and around 80 Joules for 60 mm thickness in comparison with the minimum value requirement of 27 J.

In Figure 11 we can observe very good elongation properties in comparison with minimum value requirement of 21%.

Table 9. *UT results*

Trial no. 1	Dimensions T x Wx L [mm]	Specification for examination	Specification for acceptance
1	22.5 x 3000 x 9000	EN10160/1999 – S1E1	EN10160/1999 **– S2E2**
2	22.5 x 3000 x 9000	EN10160/1999 – S1E1	EN10160/1999 **– S2E2**
3	60 x 3000 x 9000	EN10160/1999 – S1E1	EN10160/1999 **– S1E1**
4	60 x 3000 x 8000	EN10160/1999 – S1E1	EN10160/1999 **– S1E1**

Table 10. *Summary of sample data and presets of INSTRON testing machine*

Trial no.	1	2	3	4
Plate thickness [mm]	22.5	22.5	60	60
Section	23.7 mm x 25.1 mm	23.2 mm x 25 mm	Φ 14 mm	Φ 14.1 mm
Original Gauge Length Lo [mm]	140	135	70	70
Final Gauge Length Lu [mm]	180	181	91	95
Maximum Force Fm [N]	320	275	84	80
Flow Force F [N]	235	190	57.5	65
Z Section [mm]	Φ6	Φ6	Φ10	Φ10

Table 11. *Mechanical properties result after tensile test*

Trial no.	1	2	3	4
Tensile Strength [MPa]	538	474	546	513
Yield Stress [MPa]	395	328	374	416
Elongation E [%]	29	34	30	36
KV, transverse at -40 ˚C	171; 186; 191	98;115; 106	98; 92; 80	89; 102; 74
Z test 1 [%]	46; 44; 46;	65; 62; 56;	56; 51; 54;	70; 71; 71;
Z test 2 [%]	46; 41; 49	56; 60; 60	55; 59; 59	71; 71; 73

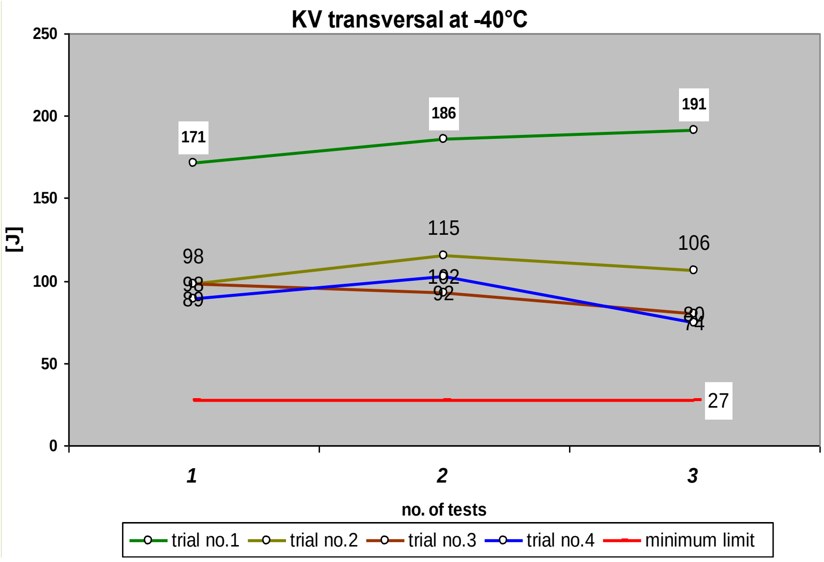


Fig. 10. Toughness results

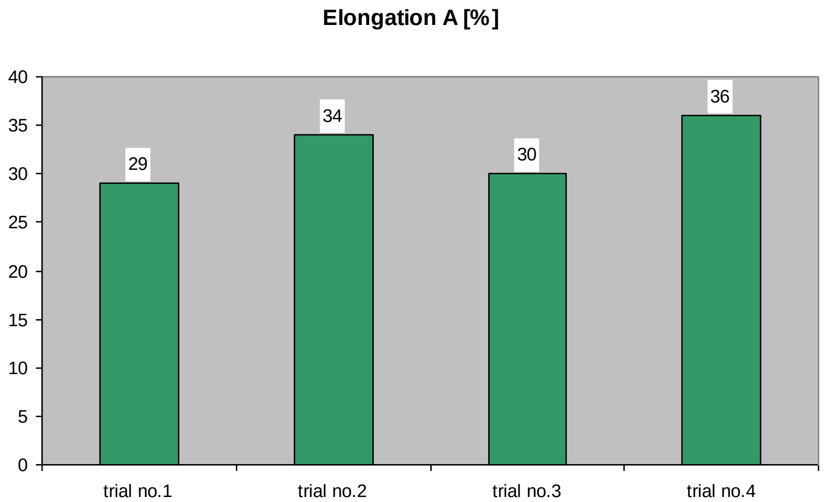


Fig. 11. Elongation result

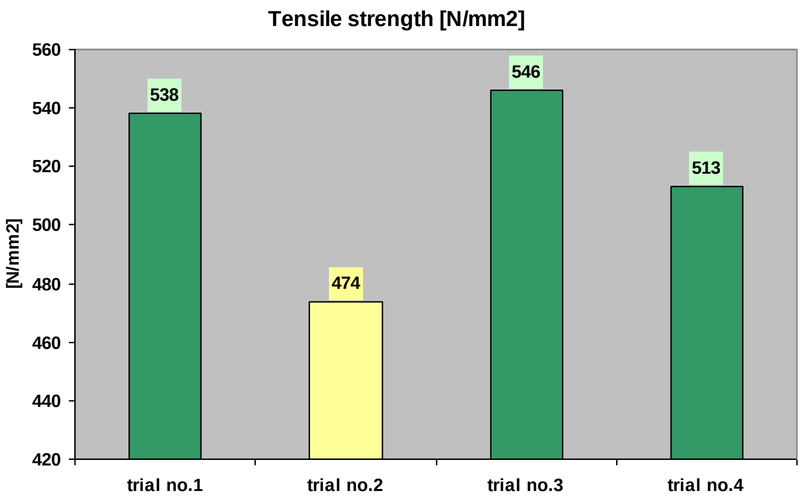


Fig. 12. Lab results of TS

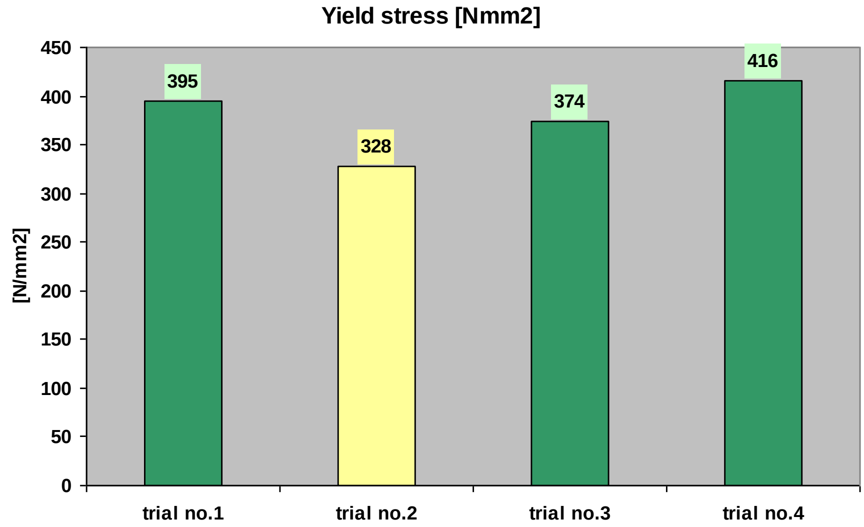


Fig. 13. *Lab results of YS*

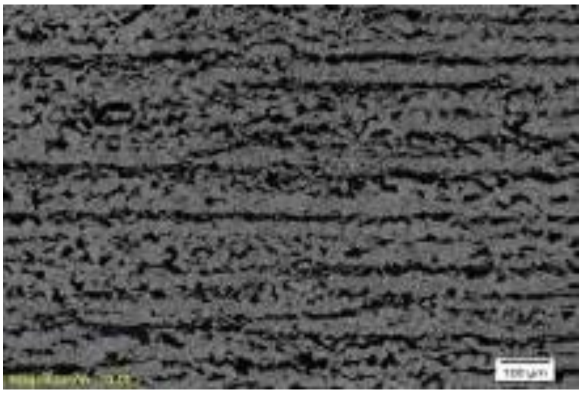


Fig. 14. *Rolling sample top surface at 100 x magnifications Ferrite-perlite relative uniform structure, grain size 8.5 - 10; KV (-40 °C) = 46 / 40 / 48 J*

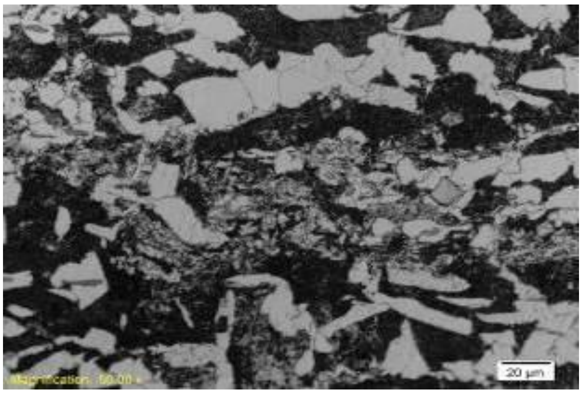


Fig. 15. *Rolling sample in middle at 500x magnifications Perlite conglomerations in large area grain size 7.5 - 9: KV (-40 °C) = 18 / 18 / 24 J*

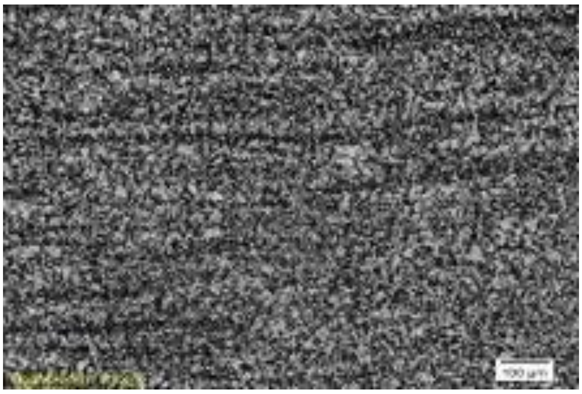


Fig. 16. *Normalized sample at 100x magnification - Ferrite-perlite uniform structure, grain size 10; KV (-40 °C) = 89 / 102 / 74 J*

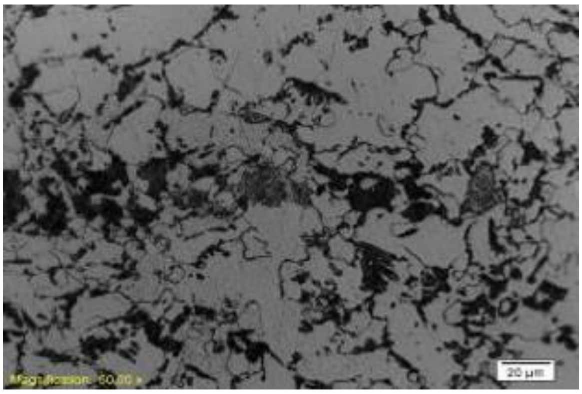


Fig. 17. *Normalized sample in middle at 500x magnification; Ferrite-perlite uniform structure, grain size 9.5; KV (-40 °C) = 52 / 48 / 58 J*

Good results on TS properties higher than 470 MPa were obtained. Except for trial no. 2, the rest of the results are very good, the TS properties on higher steel grade having limits between 485-630 MPa.

Good results on YS properties higher than 320 MPa were obtained. Except for no. 2, the rest are very good, the YS properties on higher steel grade with minimum limit being 355 MPa.

The metallography of trial no. 4 - 60 mm thickness is presented in Figures 14-19.

Fig. 18. *Rolling sample bottom surface at 100x magnification Non-uniform ferrite-perlite structure; grain size 8-9.5; KV (-40 °C) = 59 / 62 / 60 J*

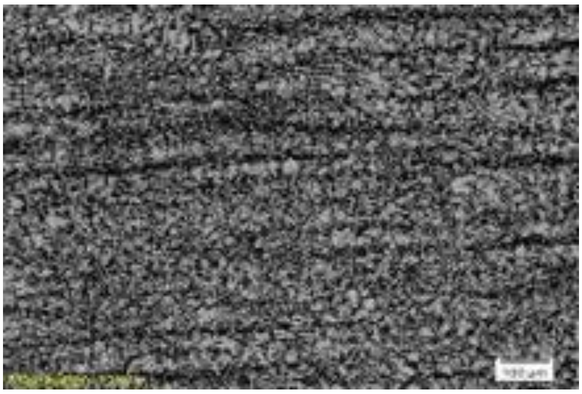


Fig. 19. *Normalized sample bottom surface at 100x magnification; Ferrite-perlite uniform structure oriented in rolling direction, grain size 10; KV (-40 °C) = 92 / 100 / 84 J*

4. Conclusions

The use of this material known as 'Z' quality steel is recommended when plate material, intended for welded construction, is subject to significant strain in a direction perpendicular to the rolled surfaces. These strains are usually associated with thermal contraction and restraint during welding, particularly for full penetration of "T"- butt welds, but may also be associated with loads applied in service or during construction. Where these strains are of sufficient magnitude, lamellar tearing may occur. Two 'Z' quality steels are specified: Z25 for normal ship applications and 'Z35' for more severe applications. As possible applications, we ca mention the frame structures, in which the plates are heavily loaded in the through-thickness direction, Beams in bridge construction, overhead bridge crane structures, ship structures, machine beds, heavily loaded structures such as crushers, propeller blade structures, oil rig cross frames, other offshore structures.

The chemical composition used in trial can be used in accordance with the followed standards ASTMA 131/2001; BV 2011; GL 2009; NKK 2008; ASME SA 612; ABS 2012; RINA 2008; LR 2013; DNV 2013; EN 10028-3-2003; EN 10025-2-2004.

Carbon equivalent was calculated according to IIW formula

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

and the following results were obtained

trial no. 1; Ceq = 0.36
trial no. 2; Ceq = 0.43
trial no. 3; Ceq = 0.41
trial no. 4; Ceq = 0.43,

offering possibilities to produce, in industrial conditions, plates with Ceq max 0.43% for both chemical compositions used in trial.

The sum of micro-alloying elements from chemical composition $\sum(Nb+V+Ti) \leq 0.12$ are in accordance with DNV rules described in the Standard for certification no. 2.9 / Approval Programme No. 301B, / Rolled ferritic steel plates, sections and bars section 4.3 and with EN 10025-3-2004 and with EN 10028/3-2009:

trial no. 1 = 0.0053
trial no. 2 = 0.0740
trial no. 3 = 0.0615
trial no. 4 = 0.1110

Nb and Ti alloying elements influence microstructure, provide fine grains in rolled state and in normalized state.

Normalizing heat treatment has higher influence in the Z trough-thickness coefficient, achieving almost double value than the minimum requirement of the highest quality Z3.5.

This trial can cover plates from structures, ships to pressure and steel grades vessels.

Trials 1 and 3 can be covered in naval section from NVE36, AH36, LRE36 below until reaching A grade. For a structure it can be achieved the S355 grade and for pressure vessels it can be achieved until P355.

Trial 2 and 4 can cover the A naval grade until A32, structural grade until S275 and pressure vessels until P275. With the combination of control rolling plus the normalizing heat treatment in the furnace, the Z35 through-thickness properties can be reached for thicknesses up to 60 mm, with the chemical composition as indicated in Table 5.

Even the matrix chemistry is only CMn without micro alloying (see trial no 1), with a good combination between control rolling and heat treatment in furnace, the Z35 properties can be achieved for thickness up to 40 mm AH32 (S275; P275).

For future research, a thickness higher than 60 mm (up to 100 mm) can be approached following the minimum micro alloyed chemistry presented in this research combined with a very good control rolling parameters and a specific normalizing heat treatment with very well defined values of time and temperatures.

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