METALLURGICAL DESIGN OF FORGED PIPES AND CONNECTING PARTS

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ABSTRACT

The results of the development of normalized (P355NH) and quenched and tempered (P355QH) forged pipes (thickness from 20 mm to 70 mm) and P355QH connecting parts (thickness up to 420 mm) are discussed. A metallurgical analysis, including the role of chemical composition and heat treatment on the microstructure and mechanical properties, was performed. The promising chemical compositions to achieve improved impact toughness at low temperature and better weldability (low C equivalent) were identified through background knowledge and application of thermal-metallurgical models. Uniform and fine ferrite-pearlite and bainitic microstructures are fundamental to achieve strength combined with good impact toughness values, even after simulated post welding heat treatment. Examples of microstructures and mechanical properties of forged pipes and connecting parts manufactured with low-C equivalent steels are given.

KEYWORDS: FORGINGS – LOW-C STEELS – NORMALIZING – QUENCHING – TEMPERING – MATHEMATICAL MODEL – MICROSTRUCTURE – STRENGTH – IMPACT TOUGHNESS

INTRODUCTION

Main Steam Lines, Main Feed Water Line, fittings, connecting parts are often made of steel grades P355NH and P355QH according to EN 10222-4. Normalizing (N) treatment can be successfully applied up to a wall thickness (WT) around 70 mm or below to achieve P355 requirements. For WT above 70 mm, quenching and tempering (Q&T) treatment is preferred/needed. The trend is to employ steels with a carbon equivalent (Ceq) content as low as possible, with benefits in terms of impact toughness and weldability. In this respect, all parts could be supplied in Q&T conditions, but this has an impact on costs. Moreover, thin and long parts can exhibit distortion after quenching, therefore higher allowance shall be foreseen (more material is needed and machining costs are greater).

1. OBJECTIVES

To establish the optimal composition range and process conditions for forged pipes and connecting parts that are normalized (WT $\leq$ 70 mm) or quenched & tempered (WT > 70 mm) to achieve grade P355NH/QH with improved impact toughness at low temperature and weldability (low Ceq).

2. APPROACH

The following approach was applied, through various sequential steps:

- Examination of the chemical composition requirements from EN 10222-4 standard and specifications from various customers.
- Analysis of the effect of single elements on steel response to process conditions, microstructure, mechanical properties.
- Definition of as narrow as possible composition ranges, obtainable with the current industrial steelmaking facilities at competitive costs (realistic composition ranges).
- Collection of experimental and calculated isothermal Temperature-Time-Transformation (TTT) and Continuous Cooling Transformation (CCT) diagrams of promising steels.
- Formulation of a tentative composition range for each element for grades P355NH and P355QH.

- Estimation of microstructure, hardness/strength levels that can be achieved through virtual simulations by thermal-metallurgical model. [1-4]
- Check of adequacy between the selected chemical compositions and the process routes to be applied, with respect to the target mechanical properties on Base Metal (BM) and after Post Weld Heat Treatment (PWHT) through laboratory tests and industrial trials.
- Fine tuning of chemical composition and process conditions.

3. ESTIMATION OF HARDNESS/STRENGTH LEVELS

Experimental Continuous Cooling Transformation (CCT) diagrams of steels with various chemical compositions (Table 1), that can be used for grades P355NH and P355QH, were collected.

Table 1 - Chemical compositions (mass percent) of the steels selected by the CCT Data Base

CHEMICAL COMPOSITION (MASS %)										
Steel	C%	Mn%	Si%	Cr%	Mo%	V%	Ni%	Cu	Nb	Ceq
A	0.13	1.20	0.21	0.14	0.04	0.060	0.14	0.21	0.025	0.40
B	0.11	1.41	0.27	0.08	0.08	0.096	0.07	0.11	0.024	0.41
C	0.10	1.19	0.25	0.14	0.14	0.040	0.37	0.20	0.025	0.42
D	0.14	1.25	0.30	0.12	0.08	0.090	0.10	0.18	< 0.005	0.43
E	0.13	1.22	0.30	0.10	0.08	0.060	0.16	0.19	0.013	0.43
F	0.14	1.41	0.22	0.12	0.17	0.096	0.15	0.15	0.022	0.45

Cooling rate (CR) values of pipes with various wall thicknesses (WT) and outside diameter (OD) were calculated by means of the thermal model after both normalizing and water quenching (Fig.1 and Fig.2, respectively).

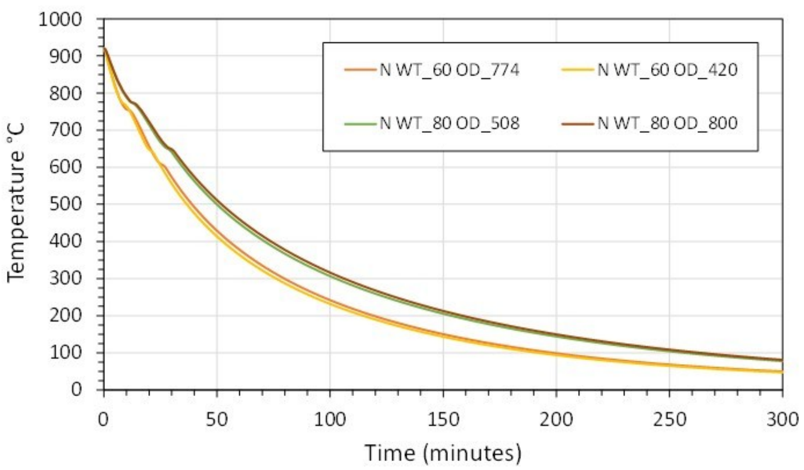
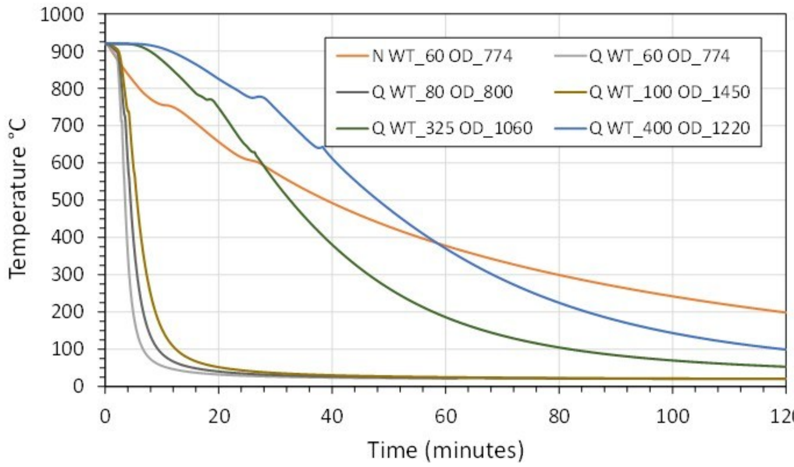


Fig.1 – Cooling paths calculated at mid-thickness during normalizing of forged pipes with different OD and WT by the thermal model

These data, combined with the information coming from the experimental CCT diagrams, were used to estimate:

- microstructure and hardness/strength after normalizing of pipes with 60 mm WT made of various steels (Table 2);
- microstructure and hardness at mid-thickness of water cooled parts with various WT (Table 3).

From Table 2, strengthening due to V precipitation can be estimated around 1500 MPa/%V for P355NH grade with Ceq = 0.40-0.43%.



b)

Fig.2 – Cooling paths calculated at mid-thickness during water quenching of parts with different OD and WT by thermal model. Also, a case of normalizing (60 mm WT) is shown for comparison.

Table 2 – Microstructure and hardness/strength levels estimated by means of CCT diagrams for pipes with 60 mm WT (CR = 0.15 °C/s) made of steels with various Ceq and V contents after normalizing

ESTIMATED STRENGTH LEVELS AFTER NORMALIZING					
Steel	Ceq (%)	V (%)	Microstructure	Hardness (HB)	Tensile strength (MPa)
A	0.40	0.060	F+P	152	510
B	0.41	0.096	F+P	170	570
C	0.42	0.040	F+P	145	485
D	0.43	0.090	F+P	168	560
E	0.43	0.060	F+P	150	500
F	0.45	0.096	F+P	190	635

Even data from literature indicate that precipitation hardening due to V addition in normalized steels (i.e. ferrite and pearlite microstructure) is reported to vary from 500 MPa/%V (for V_4C_3) to 3000 MPa/%V (for VN). [5, 6] The more carbon we have (steel F), higher is hardness (190 HB) and tensile strength (635 MPa). However, steel F has also the highest V content. We have also estimated that a steel with C = 0.15%, Mn = 1.4%, Si = 0.22%, Cr = 0.20%, Mo = 0.11%, V = 0.05%, Ni = 0.3%, Cu = 0.10%, Nb = 0.025% exhibits a tensile strength of about 590 MPa and a hardness of about 170 HB.

The strengthening due to Nb precipitates ($\Delta s_{Nb\ ppt}$) can be estimated through the following empirical equation (valid for Nb $\leq$ 0.05%; above 0.05% a saturation effect is seen):

$$\Delta s_{Nb\ ppt}\ (\mathrm{MPa}) = C * Nb_{ppt}\% \qquad \text{eq./1/}$$

where the constant C has a typical value of 1500 to 2500 MPa/%. [5, 6] The strengthening contribution due to Nb can be estimated from 30 MPa to 80 MPa when Nb content is in the range 0.020-0.040%.

When V content is reduced from 0.08% to 0.04%, it is expected to have a yield strength reduction of about 60 MPa for the normalized P355NH pipes, because volume fraction of fine precipitates, able to hinder dislocation movement and annihilation, is significantly reduced.

Considering the target tensile strength properties (Table 4) and those (Table 5) obtained on laboratory normalized specimens from forged pipes using a steel with Ceq = 0.46% and 0.08-009%V, we expect that P355NH steels with V < 0.04% can exhibit yield and tensile strength levels very close to or below the minimum desired values.

Table 3 – Microstructure and hardness estimated for various steels after water quenching (WT = 60 to 400 mm)

ESTIMATED MICROSTRUCTURE AND HARDNESS AFTER WATER QUENCHING						
Steel	Thickness (mm)	Average CR at mid-wall (°C/s)	Estimated by CCT		Estimated by model.	
			Microstructure (%)	Hardness (HB)	Microstructure (%)	Hardness (HB)
A	60	5.0	78F-7P-15M	180	82F-6P-12M	190
	100	2.3	84F-9P-7M	170	86F-9P-5M	180
	400	0.2	90F-10P	152	87F-12P-1M	160
B	60	5.0	81F-5P-7B-7M	207	74F-5P-17B-4M	203
	100	2.3	85F-8P-7M	180	80F-12P-6B-2M	190
	400	0.2	87F-10P-3M	174	82F-16P-2B-1M	170
C	60	5.0	67F-22B-11M	185	70F-6B-24M	200
	100	2.3	n.a.	n.a.	76F-8B-16M	187
	400	0.2	90F-10P	153	84F-12P-4M	160
D	60	5.0	64F-12P-13B-11M	214	66F-7P-13B-14M	220
	100	2.3	70F-13P-10B-7M	195	75F-11P-4B-10M	205
	400	0.2	81F-15P-4B	170	79F-15P-2B-4M	178
E	60	5.0	69F-3P-17B-11M	185	76F-9P-6B-9M	195
	100	2.3	80F-8P-10B-2M	172	81F-13P-2B-4M	178
	400	0.2	88F-12P	145	82F-16P-2M	160
F	60	5.0	66F-1P-21B-12M	222	44F-1P-45B-5M	224
	100	2.3	76F-6P-7B-11M	206	67F-4P-26B-3M	208
	400	0.2	84F-12P-4M	182	79F-9P-11B-1M	180

F = Ferrite; P = Pearlite; B = Bainite; M = Martensite

Table 4 – Tensile strength properties aimed on transverse specimens

AIMED TENSILE PROPERTIES							
		Room temperature (20 °C)			High temperature (300 °C)		
Grade	WT (mm)	$Rp_{0.2}$ (MPa)	Rm (MPa)	A (%)	$Rp_{0.2}$ (MPa)	Rm (MPa)	A (%)
P355NH	≤ 40 mm	≥ 335	490-630	≥ 21	≥ 225	≥ 410	≥ 21
P355QH	≥ 40 mm	≥ 320	490-630	≥ 21	≥ 215	≥ 390	≥ 21

For this reason, we prefer to maintain the vanadium content for normalized steel grade P355NH in the range 0.04% to 0.08%.

As far as grade P355QH is concerned, Table 3 gives information on typical microstructure and hardness values that are calculated at mid-wall of water cooled parts with various thickness, made of different steels with Ceq from 0.40% to 0.45% and V content from 0.04% to 0.096%. For heavy wall parts the microstructure at mid-thickness is mainly constituted of fine ferrite (80-90%), pearlite (10-15%) and small amounts of bainite and martensite (0-5%), which contribute to improving strength after tempering.

If wall thickness is reduced, higher cooling rates are developed at mid-wall. Therefore, almost all pearlite and part of ferrite are replaced by bainite and martensite; moreover, although the volume percentage of ferrite is decreased from 80-90% to 65-80%, ferrite grain is further refined. This allows us to use relatively high tempering temperatures, with benefits in terms of strength and impact toughness combination.

Ultimate tensile strengths that can be achieved after tempering of the quenched parts were also calculated for steels A, C and F, using various tempering conditions (Table 6).

Table 5 – Tensile properties obtained on laboratory specimens normalized and normalized and subjected to simulated post-weld heat treatment (SPWHT) taken from pipes at room temperature and at 300 °C (steels with Ceq = 0.46-0.48% and V = 0.08-0.09%).

TENSILE PROPERTIES ON NORMALIZED AND N+SPWHT (Lab Treatment)						
Treatment	Temp. [°C]	Testing T [°C]	Rm [MPa]	$Rp_{0.2}$ [MPa]	A [%]	Z [%]
Required →		25	490-630	≥ 335	≥ 21	Info
		300	≥ 390	≥ 230	Info	Info
NORMALIZED	930	25	541	367	29.0	69
		300	500	251	17.0	66
NORM. + SPWHT	930 + 615	25	516	348	29.2	73
		300	493	252	17.0	68
NORMALIZED	930	25	543	357	30.7	65
		300	502	253	18.0	66
NORM. + SPWHT	930 + 615	25	536	357	34.0	63
		300	488	254	17.0	69
NORMALIZED	930	25	544	371	30.3	70
		300	502	248	17.0	59
NORM. + SPWHT	930 + 615	25	526	358	29.8	73
		300	474	253	17.0	69
NORMALIZED	930	25	545	368	30.1	65
		300	505	266	17.0	64
NORM. + SPWHT	930 + 615	25	532	368	30.9	71
		300	488	253	16.0	68

Table 6 – Strength levels estimated for various steels at mid-wall (MW) after Q&T

STRENGTH LEVELS CALCULATED AT MW AFTER Q&T						
Steel	Ceq (%)	V (%)	Thickness (mm)	Tempering		Tensile strength (MPa) estimated by model
				Temperature (°C)	Time (hours)	
A	0.40	0.060	60	580	3	541
				620	3	532
			100	580	3	509
				620	3	506
			400	580	3	488
				620	3	486
C	0.42	0.040	60	580	3	592
				620	3	571
			100	580	3	561
				620	3	546
			400	580	3	529
				620	3	519
F	0.45	0.096	60	580	3	634
				620	3	611
			100	580	3	586
				620	3	573
			400	580	3	547
				620	3	540

The main aim of Table 6 was to show the changes of tensile strength calculated as a function of steel type and part thickness for a given tempering temperature. Although a tempering temperature of 580°C is not realistic (temperature of PWHT should be set at 600°C ±15°C, therefore tempering temperature shall be 620 °C or higher) it gives an idea of the maximum achievable tensile strength. Tempering at 660 °C, compared to tempering at 620 °C, gives a reduction of tensile strength of 15-20 MPa.
For Ceq = 0.42% and V = 0.04% (steel C), tensile strengths estimated by model are pretty good for thickness up to 100 mm. However, we have to warrantee strength even at 300 °C, not only at room temperature.
Table 7 shows typical yield and tensile strength values measured on Q&T forged steel parts with thickness from 200 mm to 400 mm and Ceq = 0.45% to 0.47%, with and without vanadium addition, at 20 °C and 300 °C. Even for Q&T grade, experimental data indicate that, when vanadium is very low (Ref. Q1 in Table 7), risk exists to have yield strength values at 300 °C BELW the value of 230 MPa (Table 5). Moreover, addition of V up to 0.09% still allows to achieve the desired impact toughness values at – 20 °C as shown in Table 7. Therefore, an addition of 0.05%-0.08% is also proposed for heavy wall grade P355QH.

Table 7 – Mechanical properties measured on Q&T forged steel parts (grade P355QH) with WT = 200 mm to 400 mm and Ceq = 0.45% to 0.47%, with and without vanadium addition.

MECHANICAL PROPERTIES ON Q&T PARTS											
					Tensile Testing				Impact Testing		
					T = 20 °C		T = 300 °C		T =- 20 °C		
Ref.	WT (mm)	Ceq (%)	V (%)	$T_{Tempering}$ (°C)	$Rp_{0.2}$ (MPa)	Rm (MPa)	$Rp_{0.2}$ (MPa)	Rm (MPa)	KV1 (J)	KV2 (J	KV3 (J
Q1	200	0.47	0.003	650	343	522	223	393	207	190	182
Q2	370	0.47	0.080	600	454	586	330	523	144	100	120
Q3	400	0.45	0.088	540	419	594	319	514	86	98	78
Q4	400	0.45	0.084	520	407	581	331	532	110	149	100

4. DEFINITION OF COMPOSITION RANGES

From experimental data and calculations shown previously, the following considerations can be drawn:

- For grade P355NH, maximum WT at heat treatment shall be 70 mm and a V content in the range 0.05% to 0.08% is preferred, together with Ceq of 0.44-0.46%, to develop adequate strength levels both at room temperature and at 300 °C.
- Good impact toughness can be achieved, as shown in Table 8 where experimental mechanical properties of forged pipes with WT $\leq$ 70 mm after normalizing (N) are reported for Nb-V micro-alloyed steels (Nb= 0.02%-0.04%; V = 0.08%-0.09%).
- Mechanical properties after normalizing and simulated post weld heat treatment (N+SPWHT), also shown in Table 8, indicate that SPWHT leads to a reduction in strength and even to a decrease in Charpy V-notch energy, although values are well above the requirements.
- For grade P355QH with maximum thickness of 100 mm, simulations indicate that enough strength can be developed at mid-wall after Q&T if steels have Ceq of 0.40-0.42% and V between 0.04% to 0.06%.
- For heavy wall parts with thickness up to 300-400 mm (i.e. connecting parts), even applying Q&T, rich compositions with Ceq of 0.44-0.46% and 0.06 - 0.08%V are needed to achieve a tensile strength around 540 MPa or higher and enough yield strength at 300 °C, combined with good impact toughness (Table 7).

Therefore, we selected the promising composition ranges reported in Table 9.

Table 8 – Mechanical properties measured on forged pipes (grade P355NH) with WT $\leq$ 70 mm after normalizing (N) and N+SPWHT (Nb-V micro-alloyed steels).

MECHANICAL PROPERTIES OF P355NH PIPES (WT ≤ 70 MM) AFTER N AND N+SPWHT									
Ref.	Heat Treatment	Tensile T (°C)	Rm (MPa)	$Rp_{0.2}$ (MPa)	A (%)	Z (%)	Impact Toughness, KV (J)		
							20 °C	0 °C	- 20 °C
10-B	N	25	541	367	29.0	69	226-177-244	218-201-166	141-132-142
		300	500	251	17.0	66			
10-A	N+SPWHT	25	516	348	29.2	73	212-169-201	118-108-114	100-85-70
		300	493	252	17.0	68			
20-B	N	25	543	357	30.7	65	205-206-156	154-115-121	133-115-99
		300	502	253	18.0	66			
20-A	N+SPWHT	25	536	357	34.0	63	163-181-204	133-136-141	69-74-85
		300	488	254	17.0	69			
30-B	N	25	544	371	30.3	70	204-222-156	196-162-165	113-120-105
		300	502	248	17.0	59			
30-A	N+SPWHT	25	526	358	29.8	73	148-125-215	135-98-97	106-112-88
		300	474	253	17.0	69			
40-B	N	25	545	368	30.1	65	195-149-214	144-156-144	116-137-99
		300	505	266	17.0	64			
40-A	N+SPWHT	25	532	368	30.9	71	218-207-165	120-130-132	82-68-79
		300	488	253	16.0	68			

Table 9 – Promising chemical composition ranges (mass pct) for different grades and thicknesses.

P355NH (WT < 70 mm) AND P355 QH (100 mm < WT < 400 mm													
	C	Mn	Si	P	S	Ni	Cr	Mo	Cu	V	Nb	Al	Ceq
Min	0.10	1.20	0.10	-	-	0.30	0.20	-	-	0.06	0.020	0.020	0.44
Max	0.13	1.40	0.30	0.012	0.004	0.40	0.30	0.08	0.15	0.08	0.035	0.035	0.46

P355 QH (WT ≤ 100 mm)													
	C	Mn	Si	P	S	Ni	Cr	Mo	Cu	V	Nb	Al	Ceq
Min	0.07	1.20	0.10	-	-	0.30	0.20	0.09	-	0.04	0.020	0.020	0.40
Max	0.11	1.35	0.30	0.012	0.004	0.40	0.30	0.17	0.15	0.06	0.035	0.035	0.43

In particular, the same heat can be used for both P355NH (WT $\leq$ 70 mm) and P355QH (100 mm < WT $\leq$ 400 mm). A composition with lower Ceq and V can be used for P355QH when WT $\leq$ 100 mm.

5. VIRTUAL SIMULATIONS

The chemical composition ranges proposed in Table 9, together with the WT of the parts, were considered for a sensitivity analysis. A series of virtual simulations, with parameters resembling those of industrial process to be applied, were carried out using the proprietary software Franchini-HT. [1-4] In particular, the content of the various elements was varied within the proposed ranges, maintaining Ceq within the limits shown in Table 9. The chemical composition variants and the heat treatment conditions that were simulated are summarized in Table 10, together with the calculated microstructures and tensile strength levels at mid-wall.

Table 10 – Chemical composition variants (mass pct) and simulated heat treatment conditions together with calculated microstructures and tensile strength levels at mid-wall.

CALCULATED MICROSTRUCTURES AND TENSILE STRENGTH FOR P355NH												
Grade	WT (mm)	Variant	C	Mn	Ni	Cr	Mo	Cu	V	Ceq	Microstructure (%)	Rm (MPa)
P355NH	60	V0	0.18	1.1	0.20	0.23	0.04	0.13	0.08	0.460	86F-11P-3B	551
	60	V1	0.11	1.4	0.35	0.25	0.05	0.15	0.09	0.454	86F-11P-3M	565
	60	V2	0.11	1.4	0.35	0.25	0.05	0.15	0.06	0.448	86F-11P-3M	548
	60	V3	0.13	1.4	0.35	0.12	0.05	0.15	0.09	0.448	87F-11P-2M	560
	60	V4	0.12	1.4	0.35	0.25	0.05	0.15	0.09	0.465	87F-10P-3M	568
	60	V5	0.13	1.4	0.35	0.30	0.05	0.10	0.02	0.470	87F-10P-3M	539

CALCULATED MICROSTRUCTURES AND TENSILE STRENGTH FOR P355QH													
Grade	WT (mm)	Variant	C	Mn	Ni	Cr	Mo	Cu	V	Ceq	Microstructure (%)	Rm (MPa)	
												A)	B)
P355 QH	400	V0 bis	0.18	1.3	0.21	0.20	0.02	0.09	0.09	0.480	85F-12P-3B	559	558
		V5	0.13	1.4	0.35	0.30	0.05	0.10	0.02	0.470	87F-10P-3M	534	533
		V2	0.11	1.4	0.35	0.25	0.05	0.15	0.06	0.448	86F-10P-4M	542	540
	100	V0 bis	0.18	1.3	0.21	0.20	0.02	0.09	0.09	0.480	65F-5P-13B-17M	625	606
		V8	0.09	1.3	0.40	0.26	0.14	0.05	0.06	0.453	72F-4P-13B-11M	581	569
		V9	0.09	1.2	0.35	0.25	0.10	0.10	0.04	0.401	81F-5P-2B-12M	541	533
		V2	0.11	1.4	0.35	0.25	0.05	0.15	0.06	0.448	76F-4P-2B-18M	590	577
		V1	0.11	1.4	0.35	0.25	0.05	0.15	0.09	0.454	75F-3P-2B-20M	616	598

P = 0.012%; S = 0.004%; Si = 0.22%; Nb = 0.028%; Al = 0.028%; N = 0.0080%; Al/N = 3.5; Cr+ Cu+Mo ≤0.45%; Nb+V+Ti < 0.09% or 0.12%;
$T_{austinitizing}$ = 930 °C; Holding time = 1 min/mm (for both austenitizing and tempering);
A) tempering temperature of 630 °C; B) tempering temperature of 680 °C.

The following trends can be seen from the calculation results of Table 10:

Grade P355NH (WT < 70 mm):

- C content can be reduced from 0.18% (steel V0) to 0.11-0.13% (variants V1 to V5) if Mn is increased from 1.1% to 1.3-1.4%, maintaining a tensile strength around 550-560 MPa, but V content shall be around 0.06%-0.08%: Low V concentrations (e.g. 0.02%V), even with high Ceq of 0.47% (steel V5) lead to a tensile strength decrease ≥ 26 MPa.
- Reducing C close to or below 0.10% and increasing Mn (above 1.35%) and Ni (above 0.35%), promote the formation of small amounts of martensite. Therefore, some risk can exist that small islands of high-C martensite and retained austenite (MA) could form in the segregated banded regions after normalizing, which is detrimental to impact toughness.

Grade P355QH (100 < WT < 400 mm):

- Even after water quenching, the relatively low cooling rate at mid-wall of this heavy part promotes the formation of a microstructure very similar to that of the normalized parts with 60-70 mm WT. Also strength levels are similar and not affected by tempering as the microstructure is practically constituted of ferrite and pearlite.

Grade P355QH1 (WT < 100 mm):

- The high cooling rates at mid-wall reduce the ferrite amount, whereas the volume fractions of martensite and bainite increase. Therefore, strength levels higher than those obtained after normalizing are achieved after Q&T. Increasing tempering temperature from 630 °C to 680 °C has a slight effect on tensile strength which is decreased of 10-20 MPa.

- V content can be reduced without affecting too much the tensile strength at room temperature when Ceq is 0.40%-0.43%, but a minimum content of 0.04% is recommended in order to maintain enough yield strength even at 300 °C.

For these reasons, the following limits for V are proposed:

- Grade P355NH (WT $\leq$ 70 mm) and P355QH1 (100 < WT $\leq$ 400 mm): V= 0.06-0.08%
- Grade P355QH (WT $\leq$ 100 mm): V = 0.04-0.06%.

6. EXAMPLES OF GRADES P355NH AND P355QH

In order to confirm and support the chemical composition proposed and the benefits associated with the V and Nb additions in steel, mechanical properties were measured and compared for P355NH pipes, produced using similar process conditions, but different steel designs:

- Design 1: microalloyed with Nb and V, Ceq = 0.49%;
- Design 2: microalloyed with Nb and V, Ceq = 0.46%;
- Design 3: V-microalloyed, Ceq = 0.52%
- Design 4: Nb-V free, Ceq = 0.45%.

The effect of Nb was examined comparing the mechanical properties (Table 11) of pipes with Design 1 (V+Nb steel) and Design 3 (V-steel). The selected pipes have the same WT and were manufactured using the same normalizing conditions (T = 930 °C). For each design, the minimum number of tested pipes was 5 (maximum 11).

Table 11 – Comparison of mechanical properties of normalized pipes with Design 1 (V+Nb) and Design 3 (V).

MECHANICAL PROPERTIES OF NORMALIZED PIPES WITH DESIGN 1 (V+NB) AND DESIGN 3 (V)									
Design	Ceq%	V%	Nb%	Mech. Properties	Rm [MPa]	$Rp_{0.2}$ [MPa]	A [%]	Z [%]	$KV_{-20°C}$ [J]
1 (V-Nb)	0.49	0.085	0.024	AVG.	567.4	392.4	29.4	70.4	188.5
				ST. DEV.	15.6	9.9	1.6	4.4	56.3
3 (V)	0.52	0.082	0.002	AVG.	549.3	349.8	27.2	65.7	99.4
				ST. DEV.	11.4	8.9	1.7	3.7	11.4

For a similar Ceq content (0.5%), the addition of 0.024%Nb to steels with V (0.08%) causes:

a) Strength increase (about 45 MPa for yield strength and about 20 MPa for ultimate tensile strength)
b) Slight improvement of ductility (A% and Z%), although strength is increased
c) A significant improvement of impact toughness (KV at – 20 °C), which is almost doubled (from 99 J to 188 J).

This behavior is mainly related to the better austenite refinement achieved in Nb-microalloyed steel, which leads to small and uniform ferrite grains for similar cooling conditions (same thickness and austenitizing conditions). The effect of V addition was investigated by comparison of P355NH pipes (Table 12), made of steel with 0.45-0.46% Ceq [Design 2 (Nb+V) vs Design 4 (Nb-V free)].

The addition of 0.08% V significantly increases yield strength (about 55 MPa) and tensile strength (about 40 MPa). Also, the positive effect of Nb on the impact toughness is confirmed, with an increase of about 70 J (average value).

A few examples of the final microstructure of P335NH pipes at mid-wall, using steels corresponding to Design 2, are shown in Fig.3.

Uniform and fine grained ferrite (average mean linear intercept from 7 μm to 8.5 μm) with small islands of pearlite was formed, able to develop the mechanical properties reported in Table 12 (Design 2).

Table 12 – Comparison of mechanical properties of normalized pipes with Design 2 (V+Nb) and Desing 4 (Nb-V freel)

MECHANICAL PROPERTIES OF NORMALIZED PIPES WITH DESIGN 2 (V-Nb) AND DESIGN 4 (V-Nb)									
Design	Ceq%	V%	Nb%	Mech. Properties	Rm [MPa]	$Rp_{0.2}$ [MPa]	A [%]	Z [%]	KV $_{-20°C}$ [J]
2 (V-Nb)	0.46	0.083	0.024	AVG.	536.8	360.1	30.3	65.6	141.9
				ST. DEV.	8.3	11.0	1.0	2.0	41.3
4 (V-Nb free)	0.45	0.004	0.002	AVG.	495.2	305.9	28.6	62.5	67.1
				ST. DEV.	19.1	16.6	5.3	3.1	23.4

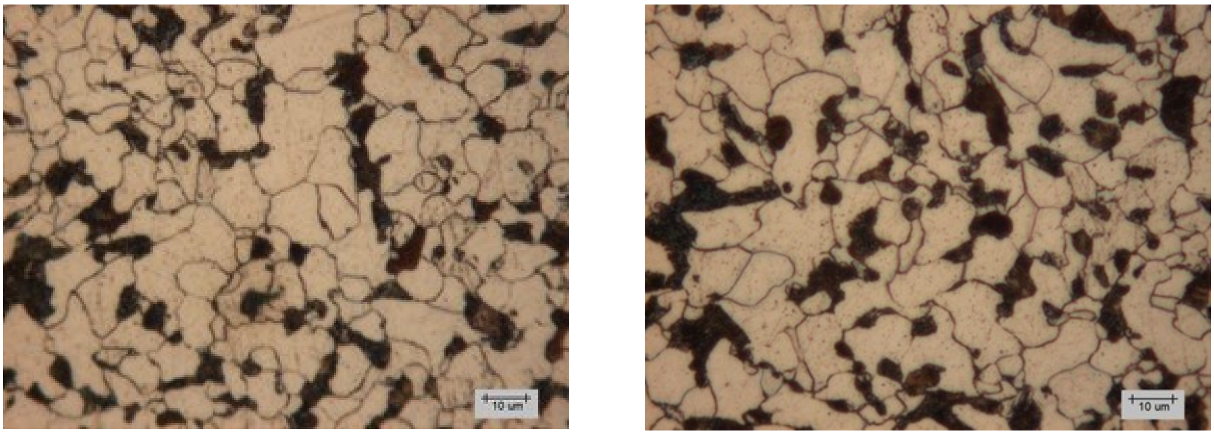


Fig.3 – Examples of fine ferrite-pearlite microstructures of P355NH pipes (steel according to Design 2)

Therefore, as far as grain size is concerned, in case of normalized materials, i.e. with a microstructure constituted of ferrite and pearlite, a ferrite grain equal to No. 9 according to ISO 643 (about 14 μm) or finer can be warranted. Moreover, Tables 11 and 12 clearly indicate that microalloying with Nb and V helps to reduce the variability of mechanical properties, although strength is increased. The reported data also indirectly indicate a good process control for normalized forged pipes as testing results show very high reproducibility.

In case of quenched and tempered (QT) materials, close to surface, where ferrite is not present, only the prior austenite grain can be measured by a selective etching able to reveal the grain boundaries of austenite before transformation to martensite/bainite.

Size of prior austenite grain, which is larger than the ferrite grain, can be warranted equal to ASTM No. 6 (40 μm), according to ISO 643, or finer for heavy wall products (WT > 300 mm). For QT products with WT < 100 mm, an austenite grain size of ASTM No. 7 (28 μm) or finer, typically ASTM No. 8-8.5 (17-20 μm) can be achieved. For heavy wall QT products (WT > 300 mm), also a ferrite-pearlite microstructure, with a ferrite grain equal to ASTM No. 9 (about 14 μm) or finer is expected at mid-wall.

Q&T Nb-V steels with 0.45%-0.47%Ceq, 0.02%-0.03%Nb and about 0.08%V can develop the required strength and toughness levels (Table 13), even in case of heavy wall (WT = 340 mm to 400 mm).

Moreover, margin exists to slightly decrease V content to 0.06% and/or increase tempering temperature up to 640-680 °C, maintaining proper strength and improving impact toughness.

7. CONCLUSIONS

For grade P355NH (WT $\leq$ 70 mm at heat treatment) and grade P355QH (100 < WT $\leq$ 400 mm) a micro-alloyed steel, with Ceq = 0.44-0.46%, Mn = 1.2-1.35%, V = 0.06-0.08%, Nb = 0.020-0.035%, and small additions of Ni and Cr (< 0.30%), was designed.

Table 13 – Mechanical properties of Q&T forged steel parts (grade P355QH) with WT from 340 mm to 400 mm.

P355QH WITH WT FROM 340 mm TO 400 mm							
REF.	WT (mm)	Ceq (%)	V (%)	Tempering T (°C)	Rm [MPa]	$Rp_{0.2}$ [MPa]	$KV_{-20°C}$ [J]
0842	370	0.47	0.080	600	586	454	144, 100, 120
0622	370	0.47	0.076	600	639	493	121, 120, 101
0019	400	0.45	0.088	540	594	419	86, 97, 78
0999	400	0.45	0.084	520	581	407	110, 129, 80

Nb = 0.02%-0.03%

Carbon content is 0.10-0.13% and Mn is maintained between 1.2% and 1.35%, because reducing C below 0.10% and increasing Mn (well above 1.4%) and Ni (above 0.30%) promote the formation of small amounts of martensite and retained austenite (MA) after normalizing. This can be detrimental to impact toughness. Moreover, 0.44-0.46% Ceq content and V within the range 0.06% to 0.08% allow to get:

- enough strength, even at 300 °C, even using tempering temperatures above 630 °C for the P355QH grade,
- good impact toughness at low temperature (- 20 °C),
- good weldability.

Another variant was designed for grade P355QH (WT $\leq$ 100 mm at heat treatment). Due to the high cooling rates at mid-wall during water quenching, lower Ceq and V contents can be used to achieve the target mechanical properties, with further benefits in terms of weldability. A micro-alloyed steel with Ceq = 0.40-0.42%, Mn = 1.1-1.35%, V = 0.04-0.06%, Nb = 0.020-0.035%, and small additions of Ni and Cr (< 0.30%) was designed through virtual simulations and laboratory heat treatments on forged parts.

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