USPOREDBA KVALITETA ZAVARA NELEGIRANIH KOTLOVSKIH ČELIKA DOBIVENA PROMJENOM POSTUPKA ZAVARIVANJA ZA KORIJENSKI SLOJ

Comparison of weld quality of unalloyed boiler steels obtained by changing arc process for the root pass

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Ključne riječi: *Hibridno elek.lučno zavarivanje, nelegirani kotlovski čelik, višeslojno zavarivanje, REL, MIG/MAG, EPP*

Key words: *Hybrid arc welding, unnaloyed boiler steel, multipass welding, SMAW, GMAW, SAW*

Sažetak

Ovaj rad razmatra utjecaj primijenjenog postupka zavarivanja na kvalitetu zavara. Kao osnovni materijali korišteni su nelegirani kotlovski čelici P265GH (EN) i S355 J2 (+ N) (EN). Izvedeno je višeslojno zavarivanje sa REL (111), MIG (131), MAG (135) i EPP (121) postupkom. Izrađeno je četiri zavarenih proba različitim postupkom zavarivanja korijenovog sloja. Korijenovi sloj u prvoj probi izveden je REL postupkom, u drugoj MIG postupkom u trećoj MAG postupkom i u četvrtom EPP postupkom. Slojevi ispune kod svih četiri proba izvedeni su EPP postupkom. Na svim zavarenim probama izvedena su radiografska i metalografska ispitivanja prije nego su podvrgnuta daljnjim ispitivanjima. Procjena kvaliteta zavara utvrđena je klasičnim mehaničkim ispitivanjima, kao što su ispitivanje zatezanjem i savijanjem, tvrdoće metodom Vickersa i žilavosti metodom Charpy. Dobiveni rezultati upućuju na to da hibridno elektrolučno zavarivanje garantira sigurnu izvedbu i opću kvalitetu zavarenih spojeva.

Abstract

This paper considers the effect of applied welding process over the weldment quality. Unalloyed boiler steels such as P265GH (EN) and S355 J2 (+N) (EN) are used as base material respectively. Welding is performed as multipass with SMAW (111), GMAW (131 and 135) and SAW (121). Four different groups of welded speciments are created, depending of the root pass. In the first, second and third group, the root pass is done with 111, 131 and 135 and filling passes with 121, while the fourth group is completely performed by 121. All welds are inspected radiographically and metallographically before submited to further evaluation. Quality assessment of weldments is determined through classical mechanical investigations such as tensile and bending test, Vickers hardness along the weldment and Charpy impact test. Attained results indicate that hybrid arc welding guarantees safer performance and general quality of welded joint.

I. Introduction

Submerged Arc Welding (SAW or 121) is one of the oldest automatic welding processes to provide high quality of weld. Typical for this process is that arc and the molten weld metal are shielded by a covering envelope of molten flux and a layer of unfused granular flux particles. The arc is completelly submerged in flux, thus the process is relatively free of radiation compared to open arc welding processes. Like Gas Metal Arc Welding (GMAW) process, SAW process uses continuous solid wire electrode that is consumed to produce filler metal. The welding currents are high (400A up to 2000A), the energy transfer is usually over 90% since losses from radiation, convection and apatter are minimal. The deposition rate is high and weld reliability is good.

SAW, due to the high melting power and the economy of the process it is very often used for producing equipment like industrial vessels, reservoirs, large pipelines [1].

Gas Metal Arc Welding (GMAW), also referred as Metal Inert Gas (MIG or 131) welding or Metal Active Gas (MAG or 135) welding, is a semi-automatic or automatic arc welding process in which a continuous and consumable wire electrode and a shielding gas are fed through a welding gun. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used. There are four primary methods of metal transfer in GMAW, called globular, short-circuiting, spray, and pulsed-spray, each of which has distinct properties and corresponding advantages and limitations. In essence, each method is defined primarily with the currents range and limited with welded thickness.

GMAW is currently one of the most popular welding methods, especially in industrial environments. Less distortion, no slag removal required, high weld metal deposition rate, high weld quality, precise operation, etc., is typical for this process [2]. However, for more demanding applications like p. vessels, this process should be strickly controled because of lack of fusion [3] type of defect which are more comon for GMAW that with many other welding methods. Unlike welding processes that do not employ a shielding gas, GMAW is rarely used outdoors.

Shielded Metal Arc Welding (SMAW or 111) is a metal joining technique in which the joint is produced by heating the work piece with an electric arc set up between a flux coated electrode and the work piece. This process is highly versatile and can be used extensively for both simple as well as sophisticated jobs. Main advantage is that it's the simplest of all other arc welding processes. Welds with this process can be made in any position. The new equipment is often small in size and can be easily moved from one place to the other. Input process parameters like welding current, welding speed, open circuit voltage and external magnetic field are highly influencing the quality of weld joints. Also, SMAW is slower than other methods of welding (except GTAW/TIG or 141) and is more depend on the operator skill for high weld quality.

Compared to other techniques, this is the least “sanitary” and precise, meaning that it's possible to capture easily slag in the weldment. Some systems are especially susceptible and can't tolerate slag at the toes of the root pass and starts/stops [4].

Although Gas Tungsten Arch Welding (GTAW/TIG or 141) produces the best quality of welds (under certain condition) compared to other techniques, however, due to lower deposition rates than the rates possible with consumable electrode arc welding processes, it is not a standard and independent process for welding industrial vessels. Therefore, it is not considered in this paper.

Generally, when thicknesses exceed the limitation of single pass techniques, or where inability to provide accurate joint fit-up prevents the use of high current - multiple pass weldment should be applied. Multipass welding also enables a variety of weld joints and plate thicknesses to be welded with the same process and materials. In certain base materials, the multipass welding technique must be used to maintain adequate properties in the base HAZ, such as unalloyed boiler steels with fine grains.

Plate thickness: 1“=25mm;
60° bevel, 0 – 3.2mm gap;
1 pass: wire 3.2mm, 170 Amps;
2 pass: wire 3.2mm, 350 Amps;
3&4 pass: 400 Amps, 27 Volts, 40 cm/min
Remainder: 500 Amps, 27 Volts, 35 cm/min
Note: ESAB recommendations [5]

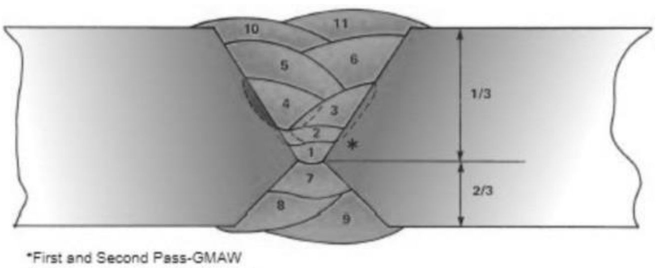


Figure 1 Multipass weld with combined welding techniques (for 1“ to 2“ plates)

In certain cases, the application of only one welding technique for multipass weldment is limited by alignment difficulties within the joint (fig.1). Therefore, a combinaton of two welding techniques can be used [5] to overcome the problem with the alignment of the geometry.

For example, pressure vessel are welded usually with SAW. In case of circumferential welds such as head-to-shell and shell butts, prepared as double bevel plate, a semiautomatic or automatic GMAW is used to handle varying fit-up in the root area as root pass process. Fill passes are then welded with SAW to provide consistent quality low cost welds. The GMAW process is the best choice for manual or automatic root or first pass procedures. The resulting weld metal is free from internal slag, and external slag is minimal making the subsequent submerged arc welds free from defects. For welding plates above 50mm thick, multipass procedures must be used.

This paper investigates the quality of the welded joint, which is obtained with a combined welding technique. In all tested variants, the fill passes are made with SAW, while the root pass was made by a different technique-GMAW (MIG/MAG) and SMAW. One test sample is welded completely with SAW and used as a referent one for comparison. Quality assessment of weldments is determined through classical mechanical investigations such as tensile and bending test, Vickers hardness along the weldment and Charpy impact test.

II. Base metal properties and weldability

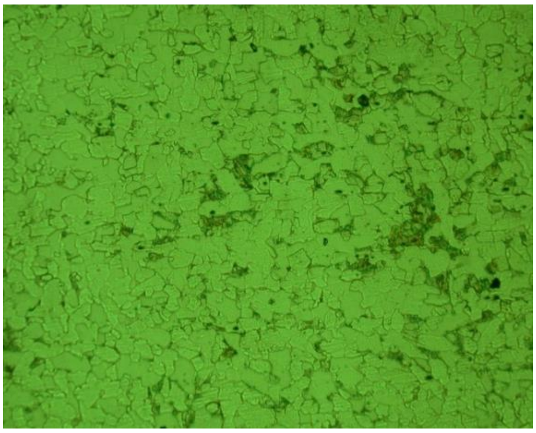
The classification of boiler (heat-resistant) steel grades for pressure vessels regarding their microstructure composition and their thermal application limits can be made both on the level of operating temperature as on its alloy content (tab.1). As it can be seen, in particular the nature of the elementary cell, i.e. whether cubic-body or face-centred cubic, affects significantly the maximum operating temperature [6].

Table 1 Classification of heat-resistant materials according to their microstructure

Heat-resistant steels and special materials				
Bcc structure^{A}				Fcc structure^{B}
Up to 400 °C	Up to 500 °C	500 to 600°C	600 to 650°C	above 700 °C
unalloyed	alloyed		High-alloyed	
ferritic-pearlitic steels, fine-grain structural steels	Mo-legierte Stähle	bainitic (martensitic) ferritic steels	Martensitic 9 to 12% chromium steels	austenitic steels, Ni and Co-materials
P235GH	16Mo3	13CrMo4-5	X10CrMoVNb9-1	X8CrNiNb16-13
P355NH	18MnMo4-5	10CrMo9-10	X22CrMoV12-1	X8NiCr32-20
No extra proven methods; higher purity; fine grain	T_R-increase^{C} through molybdenum alloying	Carbide/nitride formation + tempering	Precipitation hardening + spec. Heat-treatment	Fcc structure with high crystal recovery temperature
Guaranteed increase in temperature and creep rupture strength ⇨⇨⇨				

^{A} bcc – body-centred cubic; ^{B} fcc – face-centred cubic; ^{C} T_R - recrystallisation temperature

The materials used in this research belong to the first column of tab.1. Their exact specification, including chemical composition and mechanical properties is given in tab. 2,3,4 and 5. The base material I is in the group 1.1 according to CEN ISO/TR 15608. These materials are often subject to inspection because usually are used for shell drum and heads of the boiler, fire tubes and boiler reinforcements [7]. The microscopic structure of base material I in delivery condition is shown on fig.2.



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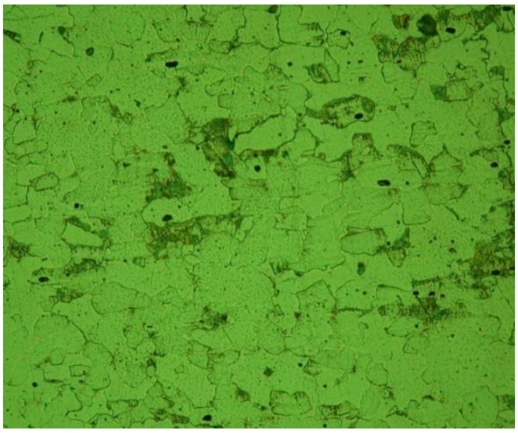

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Figure 2 Ferritic-pearlitic fine grain structure of base material I – P265GH

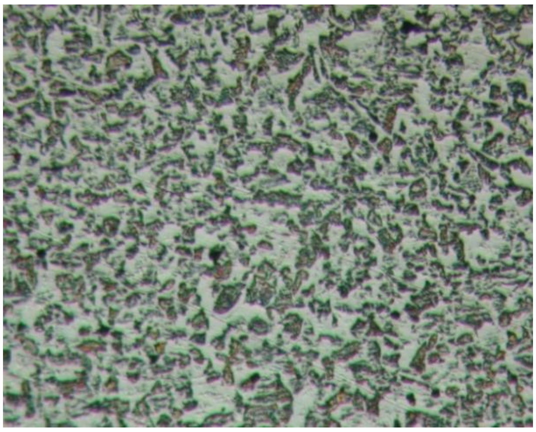
Table 2 Chemical composition of base material I

Designation: P265GH (EN 10028-2: hot rolled, N – normalized; w.no.1.0425; group 1.1) Original designation: Č.1204 (JUS C.B4.014, N – normalized state)						Thickness: δ = 12 mm
C	Si	Mn	P_{max}	S_{max}	Cr_{max}	N_{max}
<0.2	<0.35	>0.5	0.050	0.050	0.030	0.050

Table 3 Mechanical properties of base material I

Designation: P265GH (EN 10028-2: hot rolled, N – normalized; w.no. 1.0425; group 1.1) Original designation: Č.1204 (JUS C.B4.014, N – normalized state)												Thickness: δ = 12 mm
Rm [MPa]	Re [MPa], min at °C							Creep stress [MPa], min at °C				Toughness KV_{min} [J]
	20	100	200	250	300	350	400	400	425	450	475	
470	240	230	210	190	170	140	110	100	80	60	40	70

The base material II is not original boiler steel (original use is for welded precision steel tubes), but is used as a replacement material for short-term repair (patching) of equipment at elevated temperatures <300°C due to relatively high tensile and yield strenght. It belongs in the group 1.2 according to CEN ISO/TR 15608. The microscopic structure of base material II in delivery condition is shown on fig.3.



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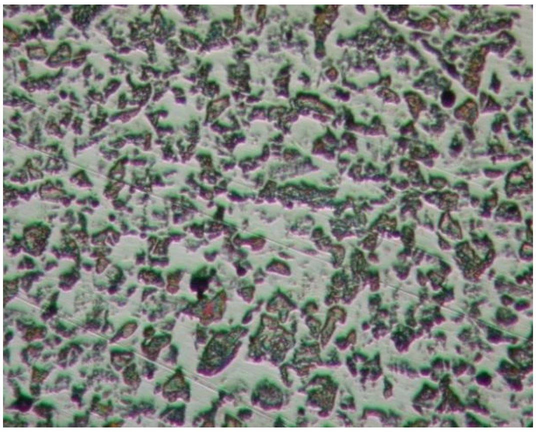

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Figure 3 Ferritic-pearlitic normalized structure of base material II – S355 J2 (+N)

Table 3 Chemical composition of base material II

Designation: S355 J2 (+N) (EN 10025-2: N – normalized; w.no. 1.0570; group 1.2) Original designation: Č.0561 (JUS C.B5.051: N – normalized state)						Thickness: δ = 16 mm
C_{max}	Si_{max}	Mn_{max}	P_{max}	S_{max}	Al	/
0.20	0.55	1.5	0.050	0.050	0.03	

Table 4 Mechanical properties of base material II

Designation: S355 J2 (+N) (EN 10025-2: N – normalized; w.no. 1.0570; group 1.2) Original designation: Č.0561 (JUS C.B5.051: N – normalized state)			Thickness: δ = 16 mm
$Rp_{0.2}$ [MPa]	Rm [MPa]	A_5 %	Toughness KV_{min} [J]
355	470-630	20	27 at -20°C

When evaluating the weldability of a steel, its chemical composition is taken as a basis. Furthermore, its toughness behaviour, as recorded in the results of the notched-bar impact test, also provides significant information about its weldability [8].

The most important element of the evaluation of a material analysis to determine weldability is carbon. Carbon content up to 0.22% is generally not critical in relation to the suitability of an unalloyed material for welding. Weldability is normal [9]. This means that the material may be welded up to a thickness of 20 mm without being preheated. Higher carbon content leads to a susceptibility to cracking in the form of hardening cracks and also hydrogen induced cracks.

III. Welding test plates – parametars of technology

For each test plate, a root pass is welded first using the appropriate welding technique. After the welding of the root pass, the other layers are welded on the SAW machine. Plates are positioned as in fig.4, to achieve the stationary mode (travel speed) of the appliance.

LINCOLNWELD 995 FLUX

LINCOLNWELD 1200 FLUX

Figure 4 Welding fill passes on test plates

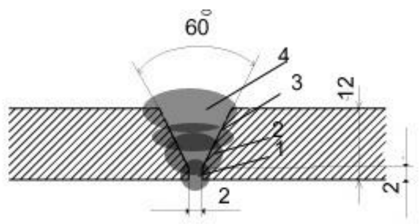
The designation of test plates is given in tab.5 and 6.

Table 5 Designation of test plates made of base material I

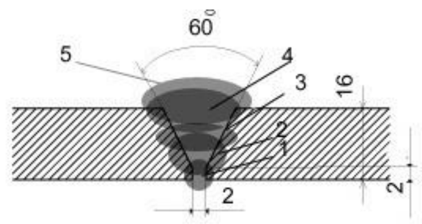
Material	Designation	Dimensions [mm]	Root	Fill	Joint prep.
P265GH	I-1	300 x 500	111-B	121	V
P265GH	I-2	300 x 500	131	121	V
P265GH	I-3	300 x 500	135	121	V
P265GH	I-4	300 x 500	121	121	V

Table 6 Designation of test plates made of base material II

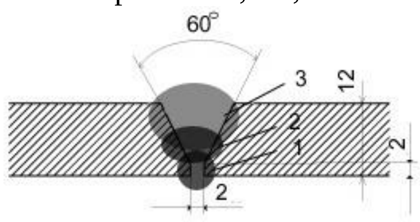
Material	Designation	Dimensions [mm]	Root	Fill	Joint prep.
S355 J2 (+N)	II-1	300 x 500	111-B	121	V
S355 J2 (+N)	II-2	300 x 500	135	121	V
S355 J2 (+N)	II-3	300 x 500	121	121	X



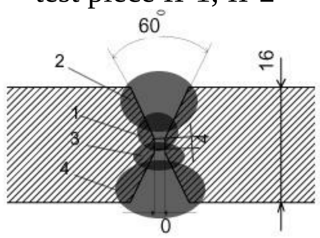
test pieces I-1, I-2, I-3



test piece II-1, II-2



test piece I-4



test piece II-3

Figure 5 Preparation of test plates weld joints

The preparation of the joints is shown in fig.5 for each individual test plate. All weld plates are welded with backing (starter) plates. As can be seen, test plate II-3 is deliberately prepared as an X-groove. This preparation represents varying fit-up in the root area, therefore alignment difficulty for SAW.

The fillers and fluxes used for welding test plates I and II are given in tab.7.The welding technology all test plate are given in tab.8 to 14.

Table 7 Filler materials and flux used for test plates I and II

Basic coated electrode EVB Ø=2.5mm, manufacturer SŽ-elektrode Jesenice, batch 063135									
%C	%Si	%Mn	%P	%S	%Cu	%Cr	%Ni	%Mo	%Al
0.08	0.6	1.0	-	-	-	-	-	-	-
Feed wire VAC60 Ø=1mm for MIG/MAG, manufacturer SŽ-elektrode Jesenice, batch 516169									
%C	%Si	%Mn	%P	%S	%Cu	%Cr	%Ni	%Mo	%Al
0.08	0.867	1.45	0.008	0.009	0.03	0.04	0.03	0.106	0.002
Feed wire for SAW EPP2 Ø=4mm, manufacturer SŽ-elektrode Jesenice, batch 771651 SAW Flux L995N, manufacturer Lincoln Electric France-EN 10204, batch 24/9669 SAW Flux AB100, manufacturer SŽ-elektrode Jesenice, batch 310016									
%C	%Si	%Mn	%P	%S	%Cu	%Cr	%Ni	%Mo	%Al
0.11	0.12	1.009	0.011	0.09	-	-	-	-	-
0.07	0.34	1.66	0.020	<0.01	-	-	-	-	-
0.07	0.34	1.66	0.020	<0.01	-	-	-	-	-

Mechanical properties of all metal weld				
Consumable	R_p [MPa]	R_m [MPa]	A_5 [%]	KV [J] at RT
EVB50	440 – 510	510 – 610	26 – 30	125 – 160
VAC60	410 – 490	510 – 590	22 – 30	80 – 125
EPP2+L995N	>380	500 – 550	>24	>90
EPP2+AB100	>380	500 – 550	>24	>90

Table 8 Parameters of welding of test plate I-1

w. pass	Current [A]	Voltage [V]	Trav. speed [cm/min]	Welding technique	Interpass temp. [°C]	Consumable	Flux
1	82	21	14	111-B	120	EVB50 Ø=2.5	-
2	420	24	50	121	120	EPP2 Ø=4	L995
3-1	480	26	40	121	120	EPP2 Ø=4	L995
3-2	520	34	40	121	120	EPP2 Ø=4	L995

Note:
- R. humidity during welding 60%
- Weld pass no. 2 is conducted with with one feed fire (α_1=90°)
- Weld pass no. 3 is conducted with with two feed fires along travel axis (α_1=90° and α_1=75°, see fig.7)

Table 9 Parameters of welding of test plate I-2

w. pass	Current [A]	Voltage [V]	Trav. speed [cm/min]	Welding technique	Interpass temp. [°C]	Consumable	Flux
1	87.5	380	-	131	120	VAC60 Ø=1	Ar
2	480	24	50	121	120	EPP2 Ø=4	L995
3-1	480	26	40	121	120	EPP2 Ø=4	L995
3-2	520	34	40	121	120	EPP2 Ø=4	L995

Note:
- R. humidity during welding 60%
- Gas protection 100% Ar, gas flow 9 lit./min
- Weld pass no. 2 is conducted with with one feed fire (α_1=90°)
- Weld pass no. 3 is conducted with with two feed fires along travel axis (α_1=90° and α_1=75°, see fig.7)

Table 10 Parameters of welding of test plate I-3

w. pass	Current [A]	Voltage [V]	Trav. speed [cm/min]	Welding technique	Interpass temp. [°C]	Consumable	Flux
1	87.5	380	-	135	120	VAC60 Ø=1	CO_2
2	480	26	50	121	120	EPP2 Ø=4	L995
3-1	480	26	40	121	120	EPP2 Ø=4	L995
3-2	520	34	40	121	120	EPP2 Ø=4	L995

Note:
- R. humidity during welding 60%
- Gas protection CO_2, gas flow 11 lit./min
- Weld pass no. 2 is conducted with with one feed fire (α_1=90°)
- Weld pass no. 3 is conducted with with two feed fires along travel axis (α_1=90° and α_1=75°, see fig.7)

Table 11 Parameters of welding of test plate I-4

w. pass	Current [A]	Voltage [V]	Trav. speed [cm/min]	Welding technique	Interpass temp. [°C]	Consumable	Flux

1	420	24	50	121	120	EPP2 Ø=4	L995
2-1	480	26	70	121	120	EPP2 Ø=4	L995
2-2	480	26	70	121	120	EPP2 Ø=4	L995
3-1	480	26	40	121	250	EPP2 Ø=4	L995
3-2	520	34	40	121	250	EPP2 Ø=4	L995

Note:
- R. humidity during welding 60%
- Weld pass no. 1 is conducted with with one feed fire (α_1=90°)
- Weld passes no. 2 and 3 are conducted with with two feed fires along travel axis (α_1=90° and α_1=75°)

Table 12 Parameters of welding of test plate II-1

w. pass	Current [A]	Voltage [V]	Trav. speed [cm/min]	Welding technique	Interpass temp. [°C]	Consumable	Flux
1	130	36	13	111-B	120	EVB50Ø=3.25	-
2	400	24	42	121	120	EPP2 Ø=4	AB100
3	500	26	34	121	120	EPP2 Ø=4	AB100
4	520	34	40	121	250	EPP2 Ø=4	AB100
5	500	28	28	121	250	EPP2 Ø=4	AB100

Note:
- R. humidity during welding 60%
- Weld pass no. 2, 3, 4 and 5 are conducted with with one feed fire (α_1=90°)

Table 13 Parameters of welding of test plate II-2

w. pass	Current [A]	Voltage [V]	Trav. speed [cm/min]	Welding technique	Interpass temp. [°C]	Consumable	Flux
1	120	380	-	135	120	VAC60 Ø=1,2	CO_2
2	380	22	42	121	120	EPP2 Ø=4	AB100
3	420	26	34	121	120	EPP2 Ø=4	AB100
4	500	28	28	121	250	EPP2 Ø=4	AB100
5	500	28	21	121	250	EPP2 Ø=4	AB100

Note:
- R. humidity during welding 60%
- Gas protection CO_2, gas flow 12 lit./min
- Weld pass no. 2, 3, 4 and 5 are conducted with with one feed fire (α_1=90°)

Table 14 Parameters of welding of test plate II-3

w. pass	Current [A]	Voltage [V]	Trav. speed [cm/min]	Welding technique	Interpass temp. [°C]	Consumable	Flux
1	390	24	44	121	120	EPP2 Ø=4	AB100
2	500	28	42	121	120	EPP2 Ø=4	AB100
3	520	30	42	121	120	EPP2 Ø=4	AB100
4	520	30	42	121	250	EPP2 Ø=4	AB100

Note:
- R. humidity during welding 60%
- Weld pass no. 1, 2, 3 and 4 are conducted with with one feed fire (α_1=90°)

IV. RT results and HAZ microstructure-metallography

Test plates after welding are subjected to radiographic test. The obtained results are enclosed in tab.15. According to the purpose, the welding technology refers to quality level C according to EN ISO 5817.

Table 15 RT results for each test plate

Test plate	Radiograph	Types of imperfections acc. EN ISO 6520-1	
I-1	S-1-1-P1	3011, 5013	Slag inclusions-linear; shrinkage groves;
	S-1-1-P2	3012, 5013	Slag inclusions-isolated; shrinkage groves;
I-2	S-1-2-P1	/	No indications;
	S-1-2-P2	5011	Continuous undercut;
I-3	S-1-3-P1	5092	Sagging;
	S-1-3-P2	502	Excess weld metal;
I-4	S-1-4-P1	2011, 402	Gas pores; incomplete penetration;
	S-1-4-P2	3012, 402	Slag inclusions-isolated; incomplete penetration;
II-1	S-2-1-P1	3012, 5092	Slag inclusions-isolated; sagging;
	S-2-1-P2	5092	Sagging;
II-2	S-2-2-P1	2011	Gas pores;
	S-2-2-P2	/	No indications;
II-3	S-2-3-P1	515	Root concavity;
	S-2-3-P2	/	No indications;
Note: EN ISO 5817: Welding. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded). Quality levels for imperfections			

With the exception of imperfection 402 – incomplete penetration for the case (test plate I-4) where the weld is fully performed with the SAW, all other imperfections are within the permissible tolerances according to EN ISO 5817 for C quality level.

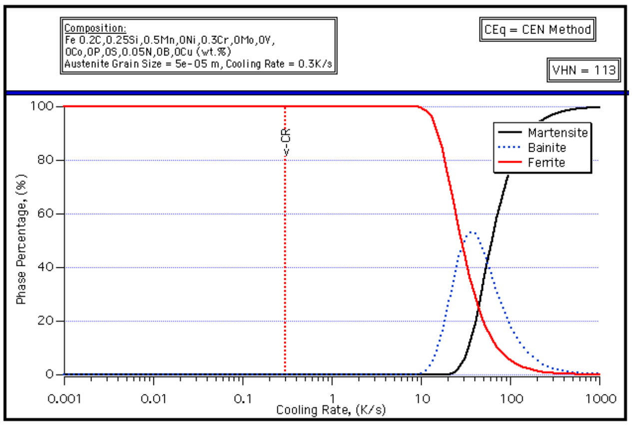
The results of RT show that the best technology in terms of quality of root pass during welding is obtained for test plates I-2, I-3 and II-2. In all other cases, there are allowed imperfections in the root pass.

The expected microstructure in HAZ can be seen from the composition diagrams (fig. 6) which give percentage representation of individual micro-constituents. They are constructed based on CCT and TTT curves. The survey is given in tab.16.

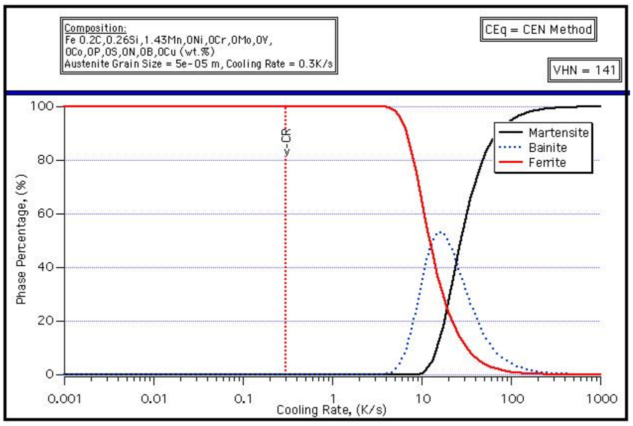
Table 16 Survey of weld and HAZ micro-constituents

Metallographic photo	Zone	Microstructure (grains)
t2 x200	Base material/HAZ (intercritical)	Polygonal ferrite & perlite
t3 x200	Fine HAZ (weld fill)	Fine ferrite & perlite
t4 x200	Coarse HAZ (weld – dillution zone)	Coarse ferrite & perlite
t5 x200	Weld (cap)	Cast microstructure
t6 x200	Weld (root)	Mixed size ferrite & perlite
t7 x200	Weld (root)/HAZ (dillution zone)	Polygonal ferrite & perlite
t8 x200	HAZ (root)/BM (BM and tempered)	Polygonal ferrite & perlite

In all test plates, a ferritic – perlite structure is obtained for both materials. Total cooling time starting from austenizing temperature – 1144°K (870.85°C) is more than 300s. Therefore cooling rate is smaller than 10°K/s.



for P265GH



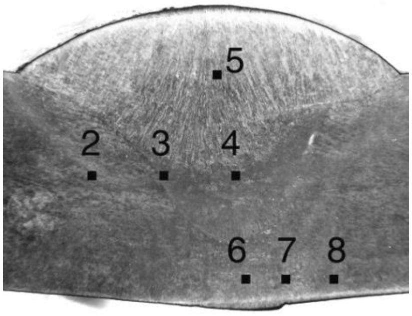
for S355 J2 (+N)

Figure 6 Phase composition diagrams for base material I and II

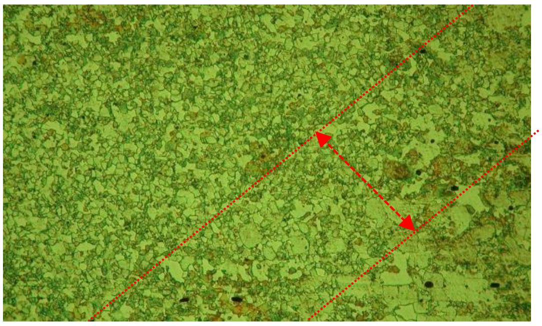
Tab. 17 shows micro – photos of the etched weld and HAZ per working point for only I-1 test plate in order to save space. In all cases of welded test plates, for both base materials I and II, the microstructure has no undesirable structures such as un – tempered martensite.

In practical use, multi-pass welding is adopted to replace single-pass welding for it can restore the unbalanced microstructure.

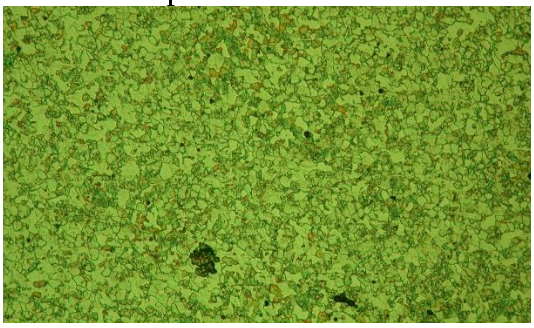
Table 17 Micro-photos x200 of HAZ zones



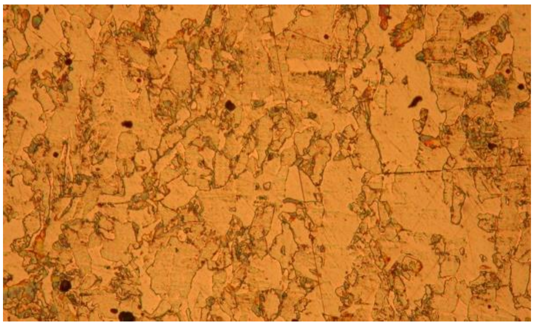
Micro-photo location scheme



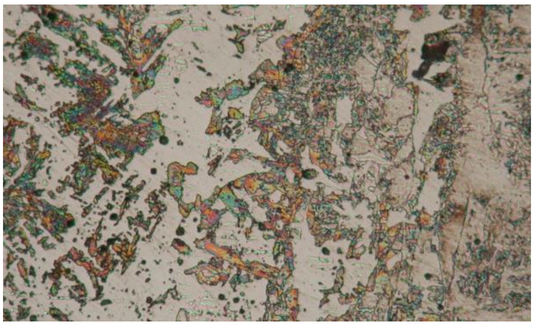
t2x200



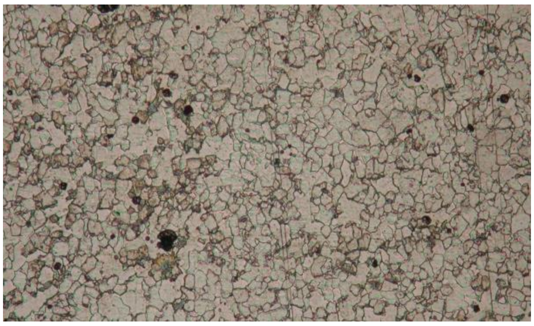
t3x200



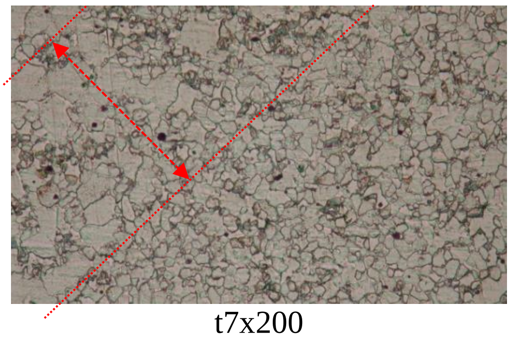
t4x200



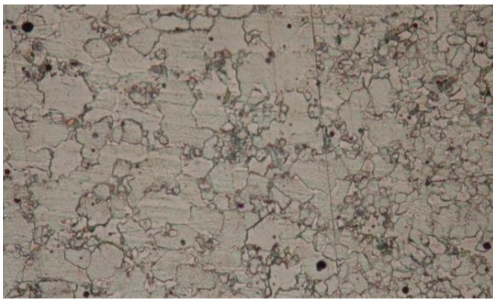
t5x200



t6x200



t7x200



t8x200

V. Results from mechanical tests

Mechanical tests that were carried out on plates samples are tensile test (EN ISO 5178), bending test (EN ISO 5173), toughness test (EN ISO 9016) and hardness test (EN ISO 9015-1).

Tensile and bending test are performed on one universal testing machine SKF COMPAGINE type U7DE700. Toughness test is performed on Charpy impact tester TESTWELL OTTO WOLPERT WERKE type PW15. Hardness test is conducted on combined tester for Brinell/Vickers method OTTO WOLPERT WERKE type DIA TESTOR ZRcS.

Samples used for examination are flame cutted from test plates (fig.7), and machined to final dimensions. Final size of test samples are given on fig.8 – 11.

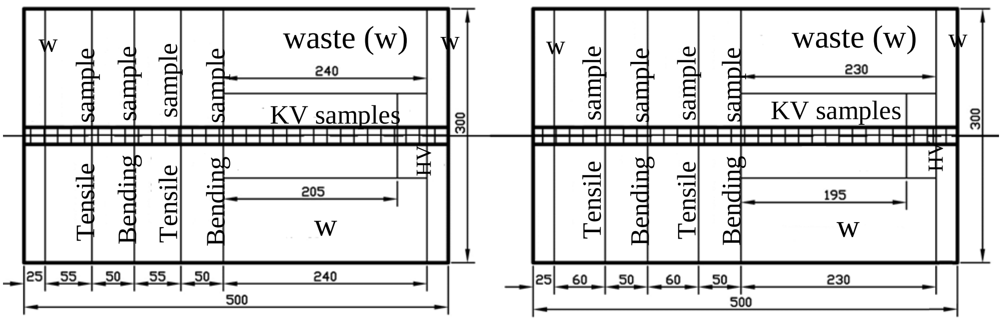
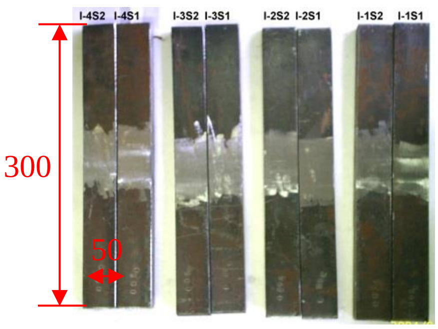


Figure 7 Cutting scheme of samples from test plates (left: BM I ≠12mm, right: BM II ≠16mm)



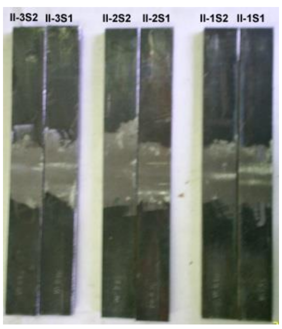


Figure 8 Bending samples – grinded cap and root (left: BM I, right: BM II)

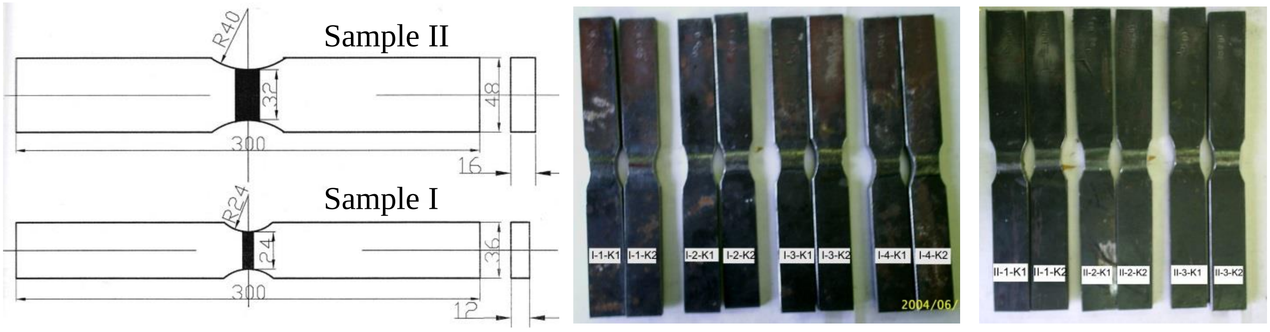


Figure 9 Tensile samples – grinded cap and root (left: BM I, right: BM II)

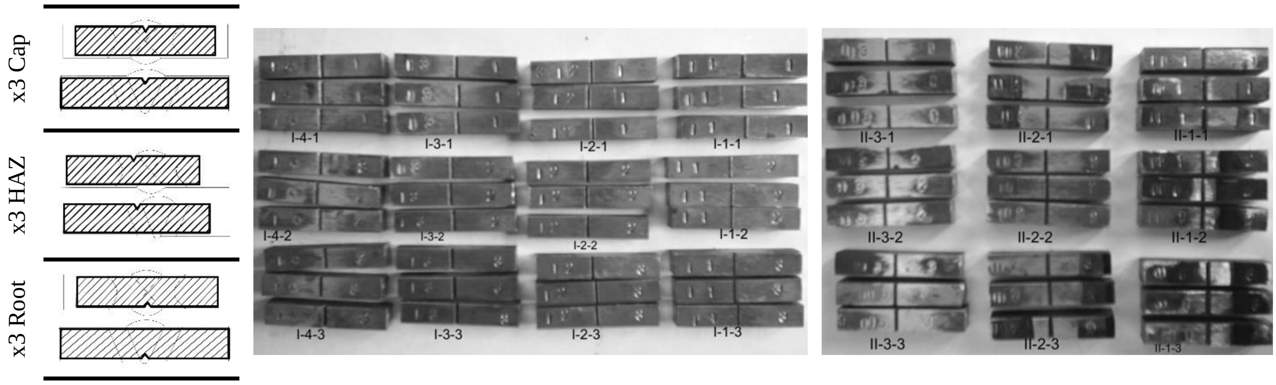
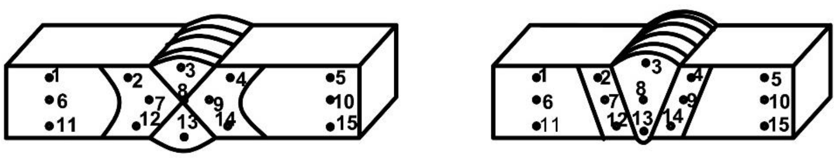


Figure 10 Impact test samples V2 notch (cap, HAZ, root samples)

Samples I and II

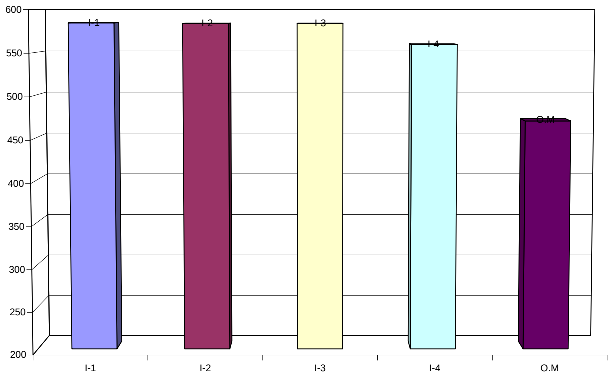


Measuring order

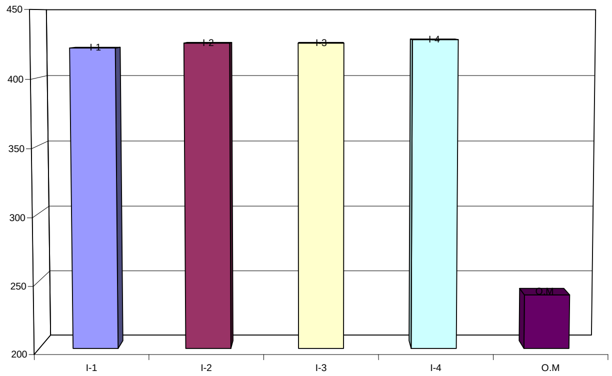
Figure 11 Hardness samples and measuring order

The results of the mechanical tests are given in the diagrams below. Diagrams 1 and 2 refer to a tensile test for base materials I and II, fig.12 refers to a bending test, diagram 3 refers to a toughness tests and a diagram 4 for testing the hardness through the welded joint (see fig.11).

All mechanical tests are successful. All measured values are within the limits. The question of the best variant gets an answer in terms of quality of technology. Quality is defined overall.



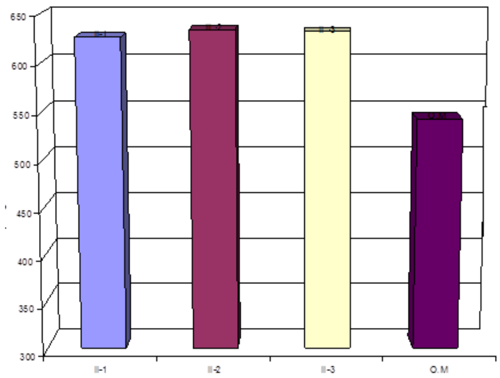
Tensile strenght



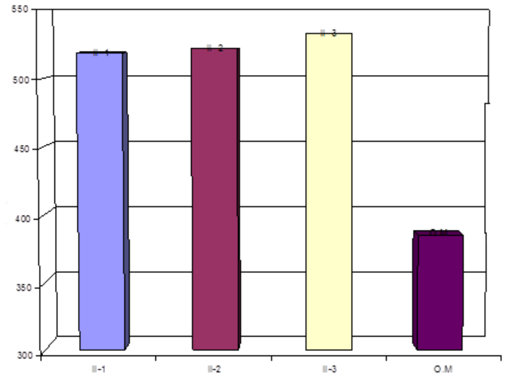
Yield strenght

| 584.5MPa | 584.0MPa | 584.0MPa | 559.3MPa | 470.0MPa | 422.0MPa | 425.6MPa | 425.5MPa | 428.0MPa | 240.0MPa |

Diagram 1 Comparison of tensile test results for BM I



Tensile strenght



Yield strenght

| 626.0 MPa | 634.0 MPa | 630.0 MPa | 540.0 MPa | 520.0 MPa | 522.0 MPa | 531.3 MPa | 375.0 MPa |

Diagram 2 Comparison of tensile test results for BM II

Figure 12 Bending test results (all samples bend to 180°)

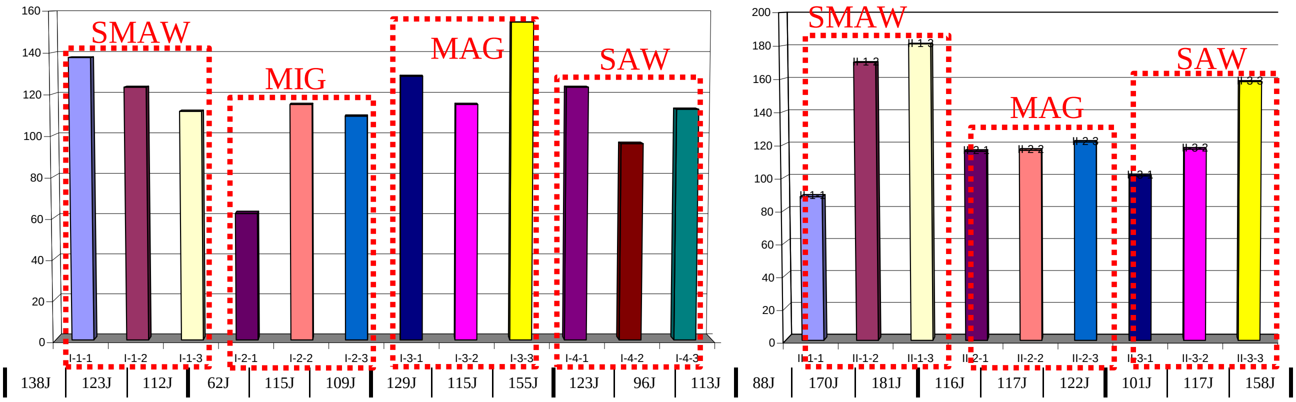


Diagram 3 Toughness test results (left: BM I, right: BM II)

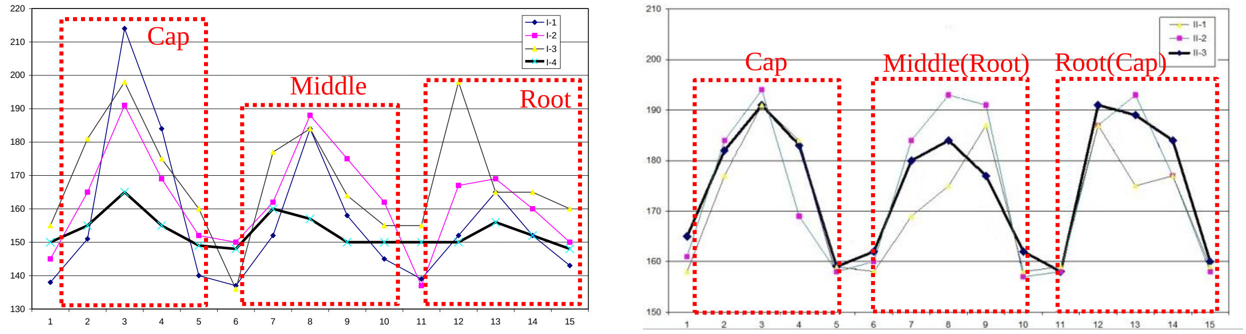


Diagram 4 Hardness test results (see fig.11)

VI. Comments and conclusion

Multipass welding produces a more favorable structure than single pass weld. The formation of a fine-grained microstructure generally results from the subsequent cooling. The transformation microstructure is caused by the fact that the amount of heat introduced by the subsequent layer austenitises the preceding layer (T > A3). Therefore, the cast structure which has low toughness is recrystalized and tempered. Therefore, it is replaced with new fine grains (tab.17, t6 insted of t5).

Hardness testing (diag.4) confirms the benefits of multipass welding ($R_m = k \cdot HV$). The maximal allowed hardness is calculated based on the chemical composition and for low alloyed steels is HV_{max}=350. Test results show that measured values are <350 (no unbalanced microstructure).

Radiographic tests confirm that the technology with hybrid arc welding where the root is performed with uncoated electrode and without flux, gives a pure root without any non-metallic inclusions (tab.15). Essecially in case with alignment difficulty (fig.5, joint II-3).

The boiler steels are used at elevated temperatures. At high temperatures, mechanical properties degrade, primarily tensile and yield strength, as well as modul of elasticity. It is therefore important that the joint is welded with techology that will provide strength properties. Diagrams 1 and 2 show that better results are obtained with the hybrid arc welding.

The results for toughness are above the permissible limits (27 J at 20°C). Toughness is not a problem at elevated temperatures. Therefore, in the given case, it is not a decisive criterion.

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