Comparative Study on the Weldability of Different Shipbuilding Steels

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Abstract

A comparison of the welding performance of ship hull structural steels has been made. The weldability of steels especially designed for laser processing was compared to that of conventional hull and structural steels with plate thicknesses up to 12 mm. Autogenous laser beam welding was used to weld butt joints as well as skid and stake welded T-joints. The welds were assessed in accordance with the document "The Classification Societies' Requirements for Approval of CO_2 Laser Welding Procedures". Small imperfections in the weld only grew slightly in root bend tests and they only had a minor influence on the fatigue properties of laser fillet welded joints. In Charpy impact tests, the 27 J transition temperature of the weld metal and HAZ ranged from below -60 to -50°C. The amount of martensite in the weld metal depended on the carbon equivalent of the steel with the highest amounts and highest hardness levels in conventional EH 36 (389 HV 5). Thermomechanically rolled steels contained less martensite and showed a correspondingly lower maximum hardness.

Key Words : Laser welding, CO_2 laser, Hull structural steel, Mechanical properties, Fatigue toughness.

1. Introduction

The increased interest in the use of laser welding in the European heavy mechanical and automotive industries together with the increasing numbers of laser installations have created demands to develop steels with better laser weldability. The development of laser weldable steels began with the collaborative project "Laser Welding in Ship Constructions" and the document "Classification Societies' Requirements for the Approval of CO_2 Laser Welding Procedures"1). According to this document, the chemical composition of the laser weldable hull structural steels L 24 and L 36 with a thickness of up to and including 12 mm should fulfil the following requirements: C £ 0.12 %, CEV £ 0.38, Pcm £ 0.22, P £ 0.010 % and S £ 0.005 %. For reduced welding speeds, e.g. 0.6 m/min for a thickness of 12 mm and 2.0 m/min for thicknesses £ 6 mm, the following deviations from the specified limits may be accepted: C £ 0.15 %, P £ 0.015 % and S £ 0.010 % for thicknesses £ 12 mm, and S £ 0.017 % and P £ 0.018 % for thicknesses £ 6 mm.

In earlier research work carried out on the RAEX LASER series of laser cutting steels the requirements for good laser cutability and laser weldability were found to be similar2). The good fatigue strength of laser welded butt and T-joints can be a significant benefit when using laser welding despite the possible presence of internal imperfections in the welds2). This paper extends that work to greater plate thicknesses, covering the laser weldability of RAEX LASER steels and comparing them to the conventional hull structural steel grades D and EH 36.

2. Test plates

The 12 mm thick test plates were all produced on a plate mill. They included the RAEX laser cutting grades S275 LASER and 420MC LASER as well as conventional hull structural steel grades D and EH 36 for comparison. The contents of the elements that have a major influence on laser weldability are given in Table 1. The bold values highlight the cases where phosphorus and sulphur exceed the values specified for laser weldable hull structural steels for thicknesses up to 12 mm1). The steels used for comparison purposes are alloyed with silicon.

3. Laser welding of test pieces

A CO_2 laser with a nominal output power of 20 kW was used and the power levels applied during the trials are listed in Table 2. The beam was moved along the work pieces by a gantry robot with an active beam

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Table 1 Ladle analyses of the plates (wt.%)

Steel grade	C	Si	Mn	P	S	Al	Micro-alloying	P_{cm}	CEV
RAEX S275 LASER	0.08	0.02	1.40	0.010	0.005	0.047	–	0.16	0.33
Grade D	0.12	0.21	0.67	0.010	0.011	0.029	–	0.17	0.25
RAEX 420MC LASER	0.08	0.02	1.38	0.010	0.005	0.037	Nb+V	0.16	0.33
Grade EH 36	0.11	0.43	1.35	0.013	0.007	0.038	Nb+V	0.20	0.36

CEV = C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15, P_{cm} = C+Si/30+(Mn+Cu+Cr)/20+Ni/60+Mo/15+V/10+5xB

Table 2 Materials, welding parameters, joint configurations and their classification

Steel grade	Joint [1]	P_L kW	v_s m/min	X-ray class	Imperfections
RAEX S275 LASER	12/12	16	1.5	D	Lack of fusion, cluster porosity
	12/12	12	1.0	B	Local undercut, gas pores
Grade D	12/12	12	1.0	D	Lack of fusion, Incompl.filled groove
RAEX 420MC LASER	12/12	16	1.5	D	Lack of fusion, cluster porosity
	12/12	12	1.0	D	Lack of fusion, gas pores
Grade EH 36	12/12	12	1.0	D	Lack of fusion, porosity on line
RAEX S275 LASER	12/12f	15	1.0	D	Porosity on line
	12/12bs	14	4.0	D	Scattered porosity
	12/12bs	7	1.12	D	Elongated cavities
	12/12s	14	1.4	D	Elongated cavities, scattered porosity
Grade D	12/12f	15	1.0	C	Porosity on line
	12/12bs	7	1.12	D	Elongated cavities
RAEX 420MC LASER	12/12f	15	1.0	D	Cracks
	12/12bs	14	4.0	C	Scattered porosity
	12/12bs	7	1.12	D	Elongated cavities
	12/12s	14	1.4	B	Scattered porosity
Grade EH 36	12/12f	15	1.0	D	Cracks, porosity on line
	12/12bs	7	1.12	D	Elongated cavities

[1] no = butt joint, f = stake weld, s = welding from single side, bs = welding from both sides

guiding system. To focus the beam a parabolic mirror with a deflection angle of 25° and a focal length of 715 mm was used producing a focal spot 0.8 mm in diameter. Helium with a flow rate of 40 l/min was used as an assist gas.

All samples were welded in position 1G. To make the single-sided skid welds in the T-joints, the beam axis was inclined to 8°. This became necessary to avoid lack of fusion because, due to the circular polarisation of the beam, the seam axis was straight.

Pre-tests with 500 mm long pieces were carried out to adjust the welding parameters and the seam quality. The parameters were adjusted to ensure reliable full penetration in the square butt and T-joints welded from one side. For the T-joints welded from two sides, the power was reduced to minimise the overlap of the seams. For the stake welds, the parameters were chosen to obtain a penetration depth of some 15 mm to ensure a sufficiently large cross section at the joint. The proof samples were 1500 mm long as required by the standard 1). Fixing the parts was done by mechanical clamping jigs as commonly used in the welding of large parts. Prior to welding, the parts were tacked using the same laser at reduced power.

4. Non-destructive testing

The test welds were inspected visually according to SFS-EN 970 using the approval criteria in EN ISO-13919-1, 1996 "Welding – Electron and laser beam welded joints – Guidance on quality levels for inspections – Part 1: Steel" 3) (B = stringent, C = intermediate and D = Moderate). 100 % X-ray inspection was carried out for all butt welds, but only 10 % were inspected for each T-joint.

5. Mechanical properties and metallography

Mechanical property testing and metallography were carried out according to reference 1 and consisted of tensile, bending and Charpy V impact tests, hardness measurements, macro-etching and micro-etching.

The tensile properties of the laser butt welds tested using transverse specimens fulfilled the tensile strength requirements specified for the base plate. All welds broke in the base plate.

Bending tests were carried out according to the standard SFS-EN 910 using longitudinal and transverse face bend specimens and longitudinal root bend specimens. The specimens were bent over a mandrel with a diameter 3.5 times the specimen thickness to an angle greater than the specified requirement of 120°. The small imperfections found in the non-destructive examinations caused small cracks in the longitudinal root bend tests.

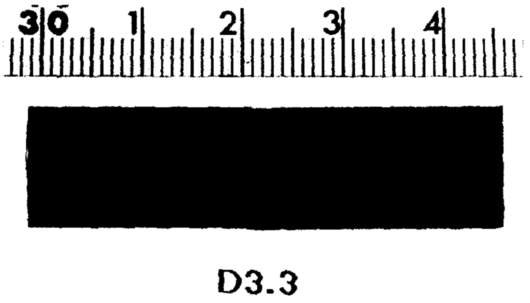

Fig. 1 Macrograph of the butt weld joint of RAEX 420MC LASER, PL = 12 kW, vs = 1.0 m/min

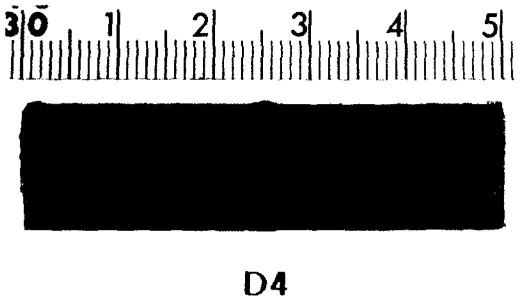

Fig. 2 Macrograph of the butt weld joint of Grade EH 36, PL = 12 kW, vs = 1.0 m/min

Fig. 3 Macrograph of the T-joint welded from both sides. RAEX 420MC LASER, PL = 14 kW, vs = 4.0 m/min

Fig. 4 Macrograph of the T-joint welded from both sides. GRADE EH 36, PL = 7 kW, vs = 1.12 m/min

Fig. 5 Macrograph of the single side welded T-joint. RAEX 420MC LASER, PL = 14 kW, vs = 1.4 m/min

Fig. 6 Macrograph of the stake welded T-joint. RAEX 420MC LASER, PL = 12 kW, vs = 1.0 m/min

Table 3 Impact transition temperatures T_{27J} and hardness

Steel grade	Joint [1]	P_L kW	v_s m/min	Plate	Weld		HAZ	
				T_{27J} (°C)	T_{27J} (°C)	HV_{max}	T_{27J} (°C)	HV_{max}
RAEX S275 LASER	12/12	16	1.5	–60	<–60	296	<–60	233
	12/12	12	1.0		<–60	305	<–60	256
Grade D	12/12	12	1.0	–36	<–60	279	–58	279
RAEX 420MC LASER	12/12	16	1.5	–60	<–60	284	<–60	231
	12/12	12	1.0		<–60	280	<–60	229
Grade EH 36	12/12	12	1.0	<–60	<–60	367	<–60	314
RAEX S275 LASER	12/12f	15	1.0		<–60	350	<–60	223
	12/12bs	14	4.0		–	340	–	315
	12/12bs	7	1.12		–	327	–	–
	12/12s	14	1.4		–	320	–	209
Grade D	12/12f	15	1.0		<–60	354	<–60	192
	12/12bs	7	1.12		–	335	–	201
RAEX 420MC LASER	12/12f	15	1.0		<–56	342	–54	226
	12/12bs	14	4.0		–	350	–	319
	12/12bs	7	1.12		–	344	–	248
	12/12s	14	1.4		–	323	–	223
Grade EH 36	12/12f	15	1.0		<–60	389	<–60	258
	12/12bs	7	1.12		–	373	–	349

[1] no = butt joint, f = stake weld, s = welding from single side, bs = welding from both sides

Table 4 Calculated fatigue classes (FAT)

Steel grade	Joint [1]	P_L kW	v_s m/min	Fatigue Class			Fatigue Class, m=3		Fatigue crack initiation
				m	$FAT_{50\%}$	$FAT_{95\%}$	$FAT_{50\%}$	$FAT_{95\%}$	
RAEX 420MC LASER	T12/12bs	14	4.0	4.73	171	152	147	100	weld/plate
	T12/12bsl	14	4.0	3.61	92	80	88	69	weld/stiffener
	T12/12s	14	1.4	2.89	110	98	112	100	weld/stiffener
	T12/12sl	14	1.4	6.94	145	125	133	84	weld/stiffener [2]
	T12/12f	12	1.0	5.09	218	192	195	145	weld/plate [3]
Grade EH 36	T12/12bs	7	1.12	2.93	116	96	118	97	weld/plate
	T12/12bsl	7	1.12	4.33	122	97	111	68	weld/stiffener

[1] T = T-joint, bs = welding from both sides, s = welding from single side, f = stake weld, l = load carrying

[2] root side in high loading and face side in low loading; [3] face side

Charpy V impact toughness testing was performed on the base plates, the butt welds and the stake-welded plates. Joints were tested at +20...–60 °C, using single-notched specimens of dimensions 10 x 10 mm with notches located in the middle of the weld and in the coarse grained HAZ, as specified in reference 1. As shown in Table 3, the impact toughness of the joints exceeded 27 J at –60 °C, except for the butt weld in hull structural steel grade D with the notch located in the HAZ, and the stake weld in steel RAEX 420MC LASER with notches located in the weld and in the HAZ.

The highest hardness values were found in the welds of T-joints as given in Table 3. The highest peak values (max. 389 in stake weld) were associated with the Grade EH 36 steel. Examples of macrographs from the joints are given in Fig. 1-6 and micrographs in Fig. 11-14.

6. Fatigue properties

The fatigue properties of typical T-joints in the higher strength steel grades RAEX 420MC LASER and Grade EH 36 were determined using constant amplitude testing under tensile loading with a stress ratio R=0.1. The T-joints are representative of joints found in shipbuilding for example, i.e. stiffener-to-plate joints in the case of fillet welds or sandwich structure spacer-to-plate joints in the case of the stake welds. Two loading cases were studied: 1) tensile stress in the plate transverse to the stiffener with no load on the stiffener and 2) tensile loading of the stiffener through the T-weld perpendicular to the unloaded plate using a frame to hold the plate close to the weld. The results were plotted as S-N curves (Fig. 7–10) and fatigue classes were calculated following Hobbacher 4), see Table 4. The fatigue classes in Table 4 are based on 50 or 95 % survival probabilities for a two-sided 75 % confidence level.

The fatigue class lines in Fig. 7-10 have been selected on the basis of the calculated FAT95% results in Table 4 and the standard lines in the document of Hobbacher 4).

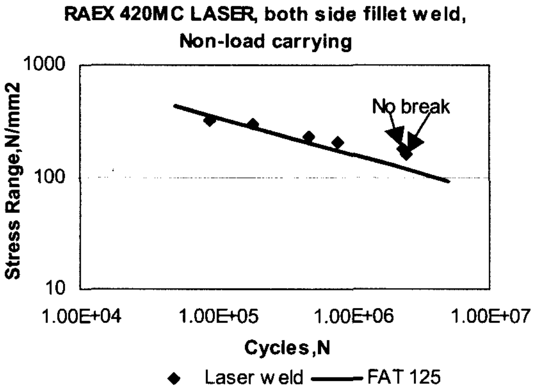

Fig. 7 Fatigue strength of the fillet weld laser-welded from both sides. RAEX 420MC LASER, non-load carrying stiffener (T12/12bs)

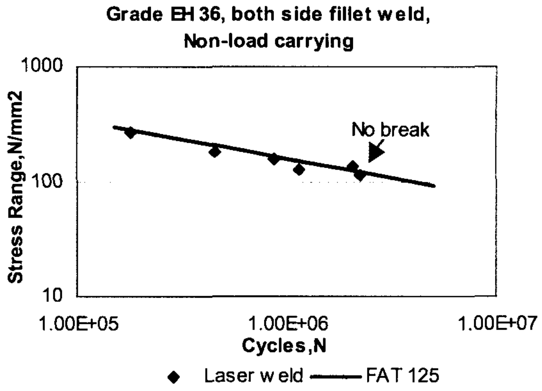

Fig. 8 Fatigue strength of the fillet weld laser-welded from both sides. EH 36, non-load carrying stiffener (T12/12bs)

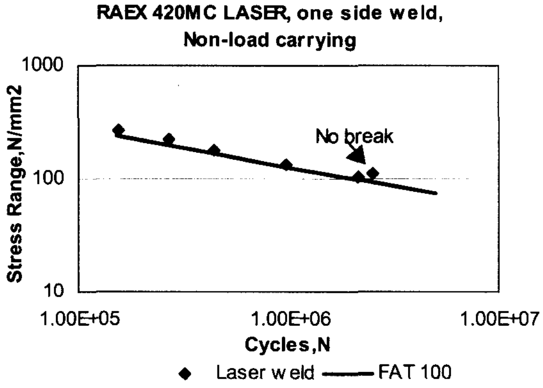

Fig. 9 Fatigue strength of the fillet weld laser-welded from one side. RAEX 420MC LASER, non-load carrying stiffener (T12/12s)

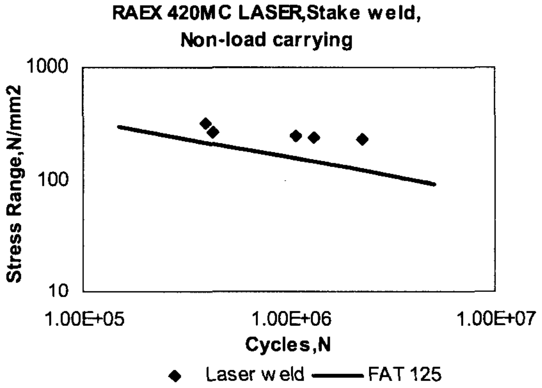

Fig. 10 Fatigue strength of the laser-welded stake weld. RAEX 420MC LASER, non-load carrying stiffener (T12/12f)

For fillet welds welded from both sides, the fatigue strength for steel grade RAEX 420MC LASER was a little better than that of steel grade EH 36 when only the plate was tensile loaded (non-load-carrying joint). However, for tensile loading of the stiffener (load-carrying joint) the opposite was true. The test results in Table 4 and in Fig. 7-10 indicate that the fatigue strength of stake welded joints were at least as good as those of fillet welded joints when tested as non-load-carrying joints.

Fatigue cracks initiated in the weld toe on the plate surfaces in the non-load-carrying joints. For the load-carrying joints welded from both sides, cracks initiated at the weld toe on the stiffener surfaces. In the non-load-carrying joints welded from one side, the fatigue cracks initiated in the root at the intersection of the weld and stiffener surfaces. In the load-carrying joints welded from one side, fatigue cracks initiated in the weld toe on the stiffener surfaces on the root side with high loading and on the face side with low loading. In the non-load-carrying stake welds, fatigue cracks initiated in the weld toe on the plate surfaces on the face side.

7. Discussion

The chosen combinations of welding parameters can be considered as suitable for the joints studied as the mechanical testing results for all the steels studied fulfilled the requirements specified in document 1. The impact toughness of the joints fulfilled the requirement of 27 J with single-notched specimens at the temperature specified for the steel grade concerned. For many joints, the impact properties were even better than those of the

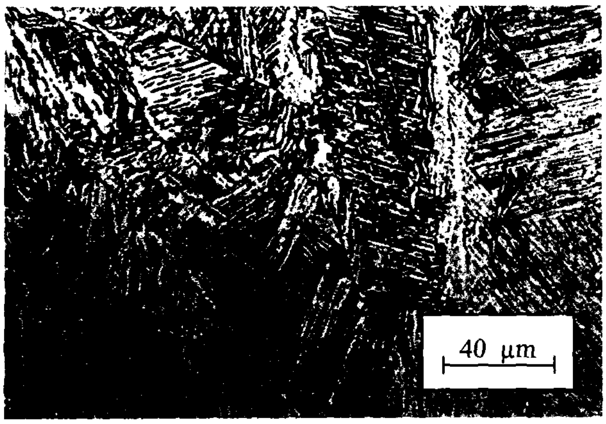

Fig. 11 Microstructure of the weld of RAEX 420MC LASER, PL = 12 kW, vs = 1.0 m/min, HVmax = 280

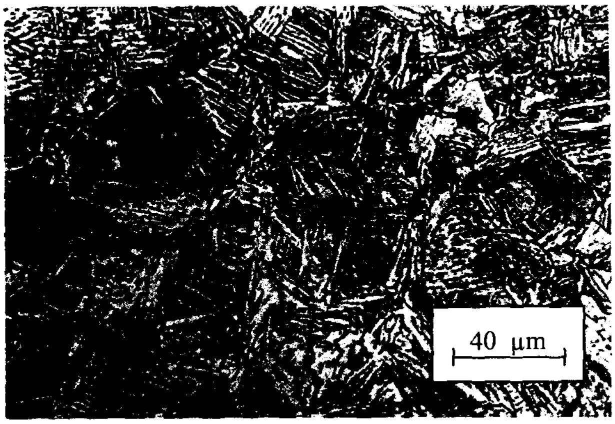

Fig. 12 Microstructure of the HAZ of RAEX 420MC LASER, PL = 12 kW, vs = 1.0 m/min, HVmax = 229

Fig. 13 Microstructure of the weld of Grade EH 36, PL = 12 kW, vs = 1.0 m/min, HVmax = 367

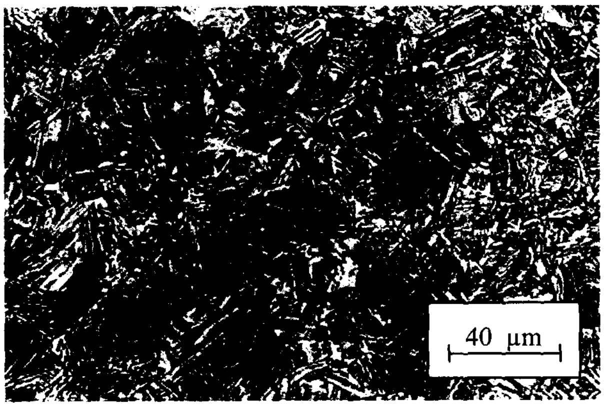

Fig. 14 Microstructure of the HAZ of Grade EH 36, PL = 12 kW, vs = 1.0 m/min, HVmax = 314

base plates. However, the evaluation of the impact toughness of laser welds should preferably be done by determining the 27 J transition temperature rather than by measuring the impact toughness at a specified (higher) temperature. In this way, the uncertainties caused by the fracture path deviating from the notched plane in the typically overmatched welds can be avoided since, at the 27 J level, fracture path deviation is avoided.

Earlier studies have indicated that decreasing the welding speed improves the impact toughness of the HAZ, but slightly impairs the toughness of the weld metal. From the microstructures, it was apparent that a lower welding speed (lower cooling rate) reduces the formation of inhomogeneous islands of martensite and upper bainite in the HAZ 2, 6). However, it increases the grain size and enhances the formation of ferrite with second phase and grain boundary ferrite in the weld metal 5).

The hardness of the joints was relatively high compared with earlier studies on laser welds. The highest peak values of 389 HV 5 from the weld and 349 HV 5 from the HAZ were associated with the T-joints of Grade EH 36 steel, which has a higher carbon equivalent (CEV = 0.36) than the other steels. The microstructure of the weld was fine-grained martensite-bainite.

The fatigue test results confirmed previous experience 2) that the fatigue strength of single and double-sided laser-welded fillet and stake welds is good. The fatigue strengths exceed the values used in shipbuilding for stiffened plates loaded transverse to fillet-welded stiffeners, i.e. Ds = 80 N/mm^2 for plate thicknesses up to 12 mm 7).

The weld toe angle has a significant influence on fatigue crack initiation and fatigue strength in fillet-welded joints. The smaller toe angle between the plate and the weld for the double-sided, laser-welded joint in EH 36 compared to RAEX 420MC LASER probably explains the differences in the fatigue strengths of the two grades when tested using transverse tensile loading of the plate (Fig. 3–4). On the other hand, for the tests where the stiffener was loaded in tension, the smaller toe angle between the stiffener and the weld in RAEX 420MC LASER probably impaired the fatigue strength compared with the similar joint in EH 36.

Concentration of plastic deformation into the sharp weld toe angle between the stiffener and the weld root explains the location of crack initiation in the fillet joint welded from one side (Fig. 5). The better fatigue strength of the laser stake welded joints was due to the more favourable geometry and dimensions of the stake welds compared to the fillet welds [2].

8. Conclusion

This research work reinforced earlier conclusions that, at the thickness of 12 mm, laser cutting grades RAEX LASER are easier to weld with lasers than conventional ship hull structural steel grades D and EH 36. This is due to the lower carbon and sulphur contents, lower carbon equivalents and good surface quality of the laser cutting grades.

Good impact toughness was achieved in butt joints and in stake welded plates tested using single-notched specimens with notches located in the weld and in the coarse grained HAZ. The 27 J transition temperatures of many joints were better than those of base plates and ranged from below −60 to −50 °C.

The relatively high hardness of the joints compared with earlier laser welding studies were due to increased amounts of martensite and bainite especially in the conventional hull structural steel Grade EH 36, which had the highest carbon equivalent (CEV = 0.36) and hardness (389 HV 5).

For plates containing non-loaded stiffeners fillet-welded from either one side or both sides as well as stake-welded plates, the fatigue strength was good, exceeding the value of Ds = 80 N/mm^2 commonly used in shipbuilding for such joints with plate thicknesses up to 12 mm.

The presence of internal imperfections in the welds has only a minor influence on the fatigue properties of laser welded joints.

Differences in weld toe angles can account for the differences in the fatigue crack initiation sites and fatigue strengths of the different laser welds.

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