MECHANICAL AND TECHNOLOGICAL PROPERTIES OF ULTRA HIGH STRENGTH OPTIM STEELS

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ABSTRACT

Ultra high strength steels designated Optim 900 QC and Optim 960 QC have been developed as 3 - 6 mm thick plate for light-weight construction, especially for the structural members of mobile equipment. The steels are based on low carbon martensite with carbon content limited to 0.11 % at most. In addition to high yield strengths of over 900 MPa, the steels exhibit very good impact toughness, i.e. around 200 J/cm^2 at –40 °C. The cold forming properties of the steels are also good due to their modified inclusions and low carbon and manganese contents. Welding can be done without preheat. The results of MAG, laser and laser hybrid welding trials are given. It is shown that acceptable weld impact toughness can be achieved at -20^{o}C using cooling times between 800 and 500^{o}C of up to about 15 s. Because of the very high strength levels and small plate thicknesses involved, the cross-weld tensile strength of butt welds is usually lower than that of the base plate, but it can be retained at base plate level by autogenous laser welding. Extensive industrial-scale trials have demonstrated that the products have good flatness and surface quality. The fatigue properties of various butt welds are described and fatigue data for laser-cut material is given. It is shown that neither pickling nor hot-dip galvanizing produce any significant deterioration in mechanical properties. The best adherence of the zinc layer is obtained with short dipping times giving a layer thickness below 100 µm.

KEYWORDS

Ultra high strength steel, Optim steel, martensite, mechanical properties, weldability, hot-dip galvanizing, fatigue

INTRODUCTION

Ultra high strength steels have been developed for lightweight construction, especially for the structural members of mobile equipment in order to reduce weight and fabrication costs as well as increase performance. Such steels are conventionally manufactured from hot rolled plate by reheating, quenching and tempering. There is, however, a demand for ultra high strength steel with improved surface quality, thicknesses not normally available as plate and tight thickness tolerances. In order to meet these demands, Ruukki Production has explored alternative ways of achieving ultra high strength levels. This resulted in two new products with yield strengths and impact toughness values that fulfil the requirements of the quenched and tempered steels S890QL and S960QL (EN 10025-6). The products have the proprietary names Optim 900 QC and Optim 960 QC, where the numbers refer to the minimum specified yield strengths of the steels. It is the purpose of the present paper to describe the results of experiments designed to determine the technological properties of these products. Issues that require further study are also mentioned.

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1. STEEL COMPOSITION & MICROSTRUCTURE

In the development of the above steels, the aim was to achieve the required yield strength levels in combination with good impact toughness and surface quality together with good technological properties such as weldability, formability and suitability for hot-dip galvanizing. In addition, consideration was given to the increasing use of laser cutting and welding.

The approach was, therefore, to base the steel composition on a low carbon content (< 0.11%) in order to ensure good weldability, flangeability and suitability to laser processing. Silicon was limited to below 0.25% in order to ensure good hot-dip galvanizing properties and to prevent any problems with red scale, which would impair surface quality. Manganese was maintained below 1.1% in the belief that, together with the low carbon content, this would keep centre-line segregation to a minimum and thereby improve the flangeability of sheared edges. Similar advantages are gained by keeping phosphorus and sulphur contents low and by modifying the sulphide inclusions using calcium treatment. These basic composition boundaries are shown in Table 1.

Keeping within these boundaries, suitable levels for other alloying elements such as chromium and molybdenum were determined with the aid of full scale rolling trials on a hot strip rolling mill. By choosing the hot strip mill as the production route, it was possible to achieve very good surface quality and thickness tolerances. This work resulted in combinations of chemical composition and processing parameters that result in fine-grained martensitic - bainitic microstructures as shown in Figure 1.

Fine tuning of the processing parameters has allowed the production of two grades with specified minimum yield strengths of 900 and 960 MPa. Other specified minimum properties are described in Table 2.

Table 1. Basic chemical composition limits and carbon equivalent values

Optim grade	C max	Si max	Mn max	P max	S max	CEV typical	CEV max
900 QC	0.010	0.025	1.15	0.020	0.010	0.46	0.51
960 QC	0.011	0.025	1.20	0.020	0.010	0.47	0.52

$$CEV = C+Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15$$

Table 2. Specified minimum tensile and impact properties (longitudinal specimens)

Optim grade	$R_{p0.2}$ min, MPa	R_m min, MPa	A_5 min, %	Impact toughness at -40°C KV min, J [1]
900 QC	900	950	8	50
960QC	960	1000	7	50

[1] Values given for 10 x 10 mm specimens. For 5 mm thick material KV min = 33 J.
For thicknesses between 5 & 10 mm, required min value linearly interpolated between 50 & 33 J.

The hot strip mill produces coils of steel that are subsequently uncoiled, levelled in a special levelling mill and cut to length. In this way plates with thicknesses of 3 - 6 mm, widths of 1000 - 1560 mm and lengths of 2 to 12 m are currently produced. As a result of the levelling

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mill treatment the plates have very low levels of internal stress as well as good flatness. As shown in the next section, the mechanical properties are also very uniform from plate to plate.

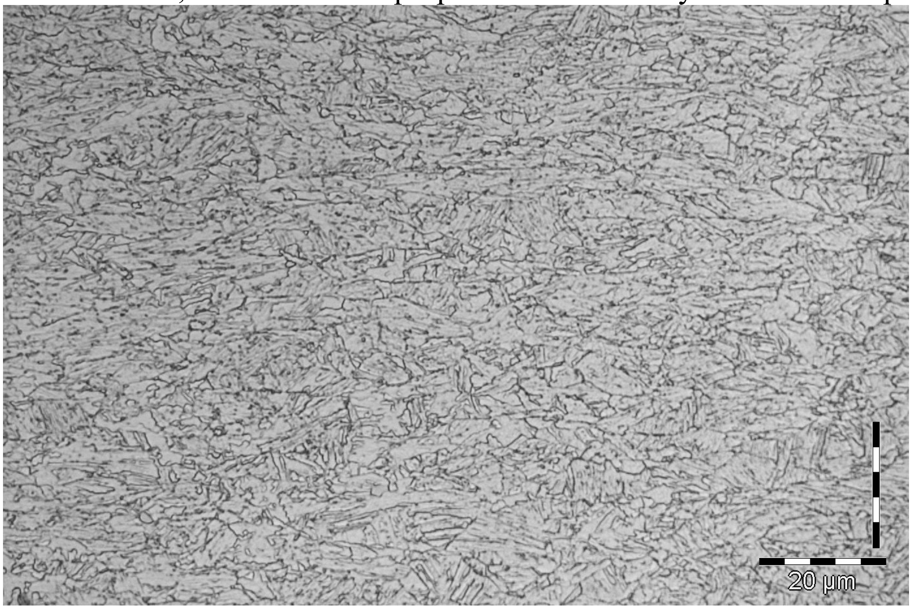

Fig. 1. Typical microstructure of the ultra high strength steel.
Light optical micrograph, nital etching. Length of micron bar 20 µm.

2. TYPICAL MECHANICAL PROPERTIES

Figure 2 shows the tensile properties of 4 mm thick plates of Optim 900 QC produced from a single coil. Tensile testing was done using specimens from a grid of 5 x 3 positions: five positions along the length of the original coil (the head and tail together with the ¼, ½, and ¾ length positions) and three positions across the width for each of the lengthwise positions (both edges and mid-width). It can be seen that the scatter in tensile properties is quite small, both along the length and across the width of the original coil.

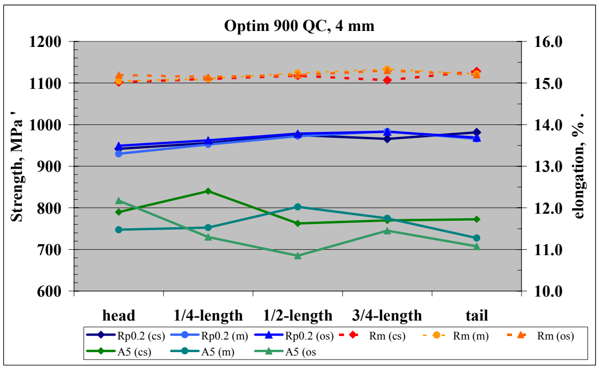

Fig. 2. Tensile properties as a function of position along the length and across the width of the coil. 4 mm plate. Each point is the average of 2 transverse specimens. From top to bottom: R_m, $R_{p0.2}$ and A_5.

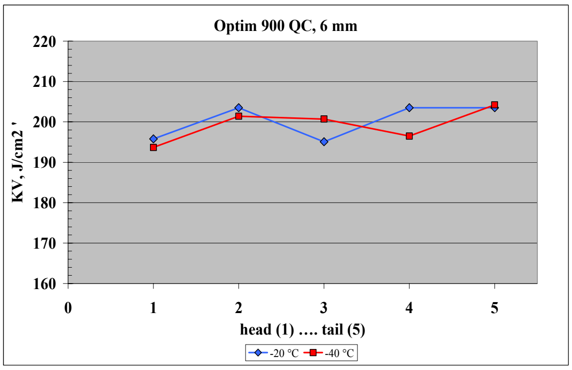

Fig. 3. Charpy V impact toughness values along the length of the coil. 6 mm plate. Each point the average of 3 transverse 6 x 10 mm specimens. Blue points -20^{o}C and red points -40^{o}C.

The material shows continuous yielding behaviour with no yield point, so that the yield stress is given by $R_{p0.2}$. Figure 3 shows that Charpy V impact toughness at -20 and -40^{o}C were also

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uniform along the length of the original strip, averaging 200 and 199 J/cm^2 respectively. All specimens showed 100% ductile fracture at both temperatures.

3. COLD FORMABILITY

Flanging in a brake press to relatively small inside bend radii is possible, but due to the very high strength of the material the equipment must be capable of handling sufficiently high loads and the tooling must be of high quality. The recommended minimum internal bend radius is 3 times the material thickness for Optim 900 QC and 3.5 times the thickness for Optim 960 QC.

Roll forming of the Optim 900 QC has been tested on the production line at Ruukki’s Toijala works. The trials were made using 4 mm thick material slit into 382 mm wide strips. The roll forming of the 13.5 m long U profiles shown in Fig. 4a succeeded without major difficulties, although the different spring-back of the ultra high strength steel compared to that of the lower strength grades normally run on the line had to be taken into account, of course. The inner radius of the 90 degree corner is 6 mm. The straightness and shape of the profiles fulfilled requirements and the roll forming process has subsequently been used to make profiles for the beams in the mobile aerial platforms shown in Figure 4.

a b

Fig. 4. U profile roll formed from Optim 900 QC (a). Beam used aerial platform (b).

Fabrication trials have also demonstrated that these ultra high strength steels can be successfully cold formed and high-frequency welded into pipes and rectangular hollow sections. The mechanical properties after the forming operation were at same level as those of the base material. However, process development is still required to achieve a high toughness in the HF weld.

4. PICKLING

Ultra high strength martensitic steels are more sensitive to hydrogen than ferritic-pearlitic steels. Consequently, tests have been performed to investigate the influence of pickling on the properties of Optim 900 QC. Pickling was done in two phases using HCl acid taken from a pickling line. The acid concentration in phase 1 was 8% and 14% in phase 2, which was

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followed by water flushing and drying. Pickling times were 20 s + 20 s for typically pickled samples and 60 s + 60 s for over-pickled samples. Slow speed tensile tests were made (0.8 mm/min) 1 hour and 1 week after pickling. Slow rate bend tests (5 mm/min) were made with 100 mm wide samples, bending through an angle of 150° over a mandrel with a radius of 2.5 x plate thickness. The results of all these tests are shown in Table 3, from which it can be seen that there is no detrimental effect of pickling on any of the tested properties.

Table 3. Effect of pickling on the mechanical properties of Optim 900 QC.
Averages and standard deviations based on 5 specimens per condition.

OPTIM RAEX 900 QC			Rp 0.2, MPa		Rm, MPa		A5, %		Bending
			long.	trans.	long.	trans.	long.	trans.	r = 2.5 t
before pickling		ave	928	923	1061	1066	12.6	11.8	ok
		std	4.2	8.6	9.4	11.9	0.7	0.8	
pickled	after 1 hour	ave	960	944	1086	1084	13.2	10.7	ok
		std	37.8	10.5	11.8	13.7	0.8	0.3	
pickled	after week	ave	944	938	1080	1084	12.8	11.8	ok
		std	7.9	7.6	4.7	8.9	0.3	0.7	
over pickled	after 1 hour	ave	932	944	1067	1086	13.1	10.4	ok
		std	3.6	24.9	6.6	20.9	0.8	0.2	
over pickled	after week	ave	949	937	1083	1074	12.1	11.8	ok
		std	8.6	11.5	12.4	10.4	0.9	0.6	

5. HOT-DIP GALVANIZING

Hot-dip galvanizing tests were made using Optim 900 QC with dipping times of 3, 6 and 9 min. All specimens were pickled in HCl for 135 min, flushed in water for 0.5 min, dipped in flux for 0.5 min and dipped in a zinc bath at 455 °C. The hammer test showed that the best adhesion of the zinc layer is obtained with the shortest dipping time, which gives a zinc layer thickness of less than 100 µm.

The effects of hot-dip galvanizing on mechanical properties can be seen in Table 4. The heat of the galvanizing process decreases the tensile strength very little, whereas yield strength is increased somewhat, giving yield to tensile ratios close to unity. As regards the thickness and quality of the zinc layer, Optim 900 QC behaves as expected for steel with a Si+P content of about 0.2 %. Hot-dip galvanizing properties fulfil class 3 of EN 10025.

Table 4. Tensile properties and zinc layer thickness after hot-dip galvanizing.

Sample		Rp0.2 MPa	Rm MPa	A5 %	Agt %	Ag %	Zn-layer µm
A_base	ave	947	1008	10.9	2.6	2.15	-
B_3min	ave	994	999	12.4	4.1	3.65	87
C_6min	ave	970	977	10.9	1.7	1.25	137
D_9min	ave	980	990	11.9	3.8	3.4	202

6. LASER CUTTING

Laser cutting is a thermal cutting method that is commonly used nowadays due to its high cutting precision. It has therefore been of interest to examine the effect of laser cutting on the

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properties of the new steels. Laser cutting tests have been made using 4 mm thick Optim 900 QC. 4 mm thick S650MC was also cut using the same parameters, for comparison. In both cases, the surface quality of the laser cut edges was good and smooth.

Figure 5 shows Vickers microhardness measurements made on sections perpendicular to the laser cut edges. The cut edge was hardened in both steels. In addition, Optim 900 QC showed a narrow softened zone (about 0.2 mm wide) between the hardened edge and the unaffected base material. The lowest hardness values were about 60 HV0.2 lower than the base material. (Due to its different chemistry, processing route and strength, S650MC shows no softened zone). The small extent of the softened zone should be beneficial to fatigue properties and improve cold formability.

The fatigue properties of laser cut materials were determined in tests at 20 Hz with a stress ratio R = 0.1. The results, shown in Figure 6, indicate that the fatigue limit for laser cut Optim 900 QC approaches 500 MPa, i.e. more than half of the yield strength.

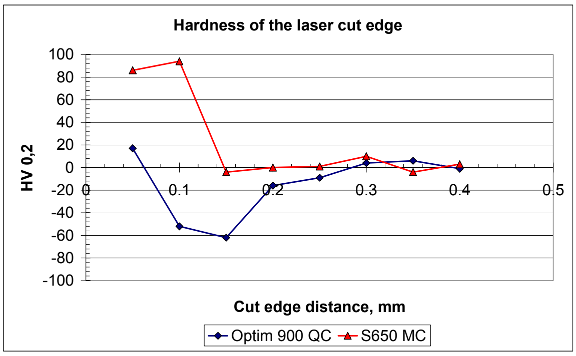

Fig. 5. Microhardness changes below laser cut edges. Zero denotes the hardness of the unaffected base material.

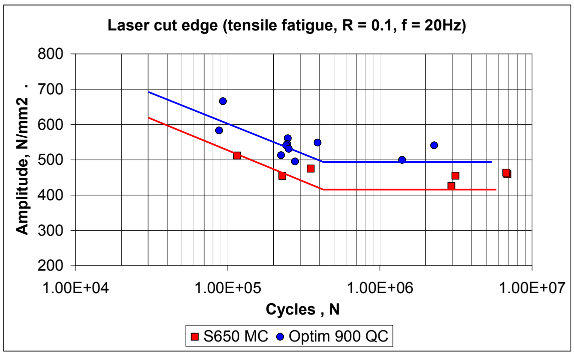

Fig. 6. S-N curves of laser cut Optim 900 QC and S650MC for comparison.

7. WELDABILITY - MAG & LASER WELDING

The weldability of Optim 900 QC and 960 QC has been investigated for 3 and 6 mm thick plates. In this thickness range, MAG welding is mainly of interest, and the effect of MAG arc energy has been studied using a 6 mm thick plate of Optim 900 QC. In addition, 3 and 6 mm thick plates of Optim 960 QC have been MAG welded at 0.5 kJ/mm. With the growing interest in laser welding in mind, 3 mm thick plates of Optim 960 QC have also been laser welded and a 6 mm thick plate of the same steel welded using hybrid laser-MAG welding.

MAG welding was done using the ESAB LAH 630 equipment of Ruukki Production. Laser and laser hybrid welding was performed using the 6 kW CO_2 laser (Rofin-Sinar 6000) and the ESAB ARISTO 2000 of the Laser Processing Laboratory of Lappeenranta University of Technology.

Butt joints in Optim 900 QC were made using 1 mm diameter ESAB OK Autrod 13.31 wire and a shielding gas comprising argon and CO_2 (M21). Milled V grooves with root gaps of 1.5-2 mm were used. Welding was carried out without preheating using interpass temperatures of 25 ºC and arc energies of 0.5 and 0.8 kJ/mm. MAG welding of Optim 960 QC was carried out using the same consumables and edge preparation, and an arc energy of 0.5 kJ/mm.

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The test plates for autogenous laser butt welding were laser cut with nitrogen and the test plates for laser hybrid welding were shear cut to 500 x 150 mm. In the autogenous laser welding, the joints were adjusted in such way that there was no air gap, and in laser hybrid welding there was an air gap of 0.25 mm between the plates. The joints were tack welded using the MAG process, the distance between tacks being approximately 100 mm. During welding the joints were clamped to the work table. Autogenous laser welding was done with the focal position on the upper surface and 25 l/min of helium as the shielding gas. In laser hybrid welding the focal position was on the surface and the stick-out was 15 mm. The shielding gas used in the laser hybrid welding experiments was 50% He + 45% Ar + 5% CO_2 with a flow rate of 30 l/min, and the filler wire used was OK 13.31 with a diameter of 1.0 mm.

The evaluation of the laser welds was carried out using both destructive and non-destructive testing in accordance with EN ISO 15614-1 and the document *”The Classification Societies’ Requirements for Approval of CO_2 Laser Welding Procedures”* issued by the ship classification societies in 1996. The destructive testing of the joints consisted of tensile and impact tests, as well as hardness measurements.

Non-destructive visual and X-ray examination showed that class B (stringent) was mainly achieved in the MAG welded joints, but class C dominated in the laser and laser hybrid welded joints. The lower quality class of the laser-based methods was due to higher porosity, incomplete filling of grooves and roots, and local lack of fusion.

Figures 7 and 8 show Vickers hardness profiles across the welds in Optim 960 QC. It can be seen that the HAZ is associated with a drop in hardness below that of the base plate. The width and depth of the softened zone can clearly be reduced by using laser or laser hybrid welding. The weld metal is approximately even matching in the case of the laser-based methods, but it is slightly under-matching in the case of the MAG weld in the 3 mm thick material.

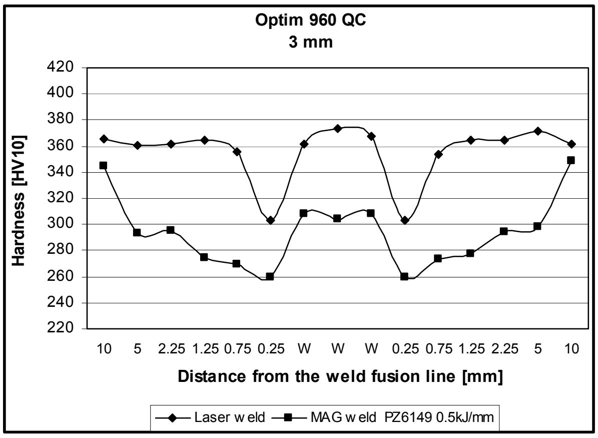

Fig. 7. Hardness profiles across 3 mm thick laser and MAG welded butt joints in Optim 960 QC. (Note that the distance scale is non-linear).

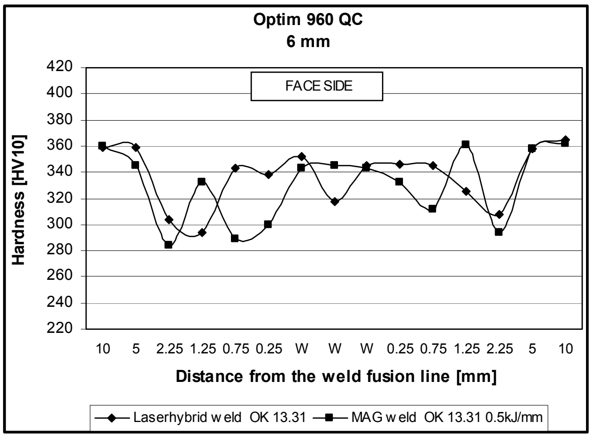

Fig. 8. Hardness profiles across 6 mm thick laser and MAG welded butt joints in Optim 960 QC. (Note that the distance scale is non-linear).

The presence of these softer zones in the welds is reflected in cross-weld tensile test properties as shown in Table 5 . The narrow, shallow soft zone in the autogenous laser weld in

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Optim 960 QC does not lower the tensile strength of the joint compared to that of the base plate. However, the MAG welds have cross-weld tensile strengths that are lower than that of the base plate. For a constant heat input (0.5 kJ/mm^2), the reduction in tensile strength increases as the plate thickness decreases from 6 to 3 mm. A similar effect can be seen on increasing the arc energy in the case of the 6 mm thick MAG welded butt joints: higher arc energy (0.8 kJ/mm) produces greater under-matching. Consequently, welding should be done with as low an arc energy as possible and any resultant under-matching taken into account at the application design stage.

Table 5. Tensile test results from welded butt joints

Optim grade	Thickness mm	Test type	Method / arc energy kJ/mm	$R_{eH/p0.2}$ N/mm^2	R_m N/mm^2	Minimum specified R_m N/mm^2
960 QC	3	Plate	-	986	1110	1000
		Weld	Laser	1014	1136 [1,2]	
		Weld	MAG / 0.5	760	870 [2]	
960 QC	6	Plate	-	1001	1111	1000
		Weld	Hybrid	803	1029 [2]	
		Weld	MAG / 0.5	843	945 [2]	
900 QC	6	Plate	-	998	1110	950
		Weld	MAG / 0.5	852	933 [3]	
		Weld	MAG / 0.8	805	892 [3]	

[1] Fracture in the weld; [2] Fracture in the HAZ; [3] Fracture location not recorded.

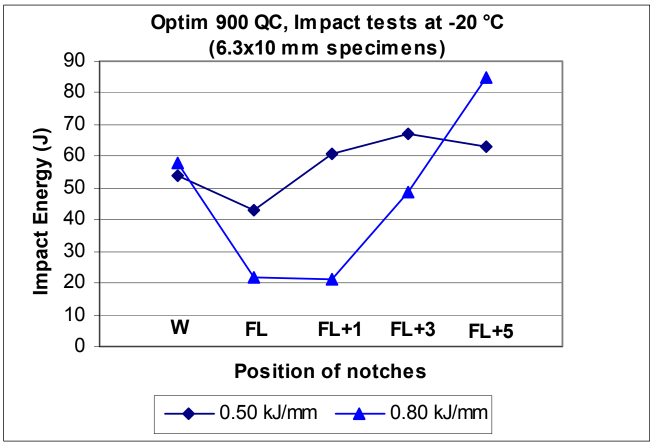

Fig. 9. Influence of MAG welding arc energy on toughness

Charpy V impact test results from the 6 mm thick butt welds in Optim 900 QC showed that the increase of arc energy from 0.5 to 0.8 kJ/mm reduces the impact toughness in the fusion line / HAZ to close to the minimum acceptable, Figure 9. It is therefore suggested that, in

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general, the arc energy for this thickness is limited to about 0.8 kJ/mm corresponding to a calculated cooling time from 800 to 500°C ($t_{8/5}$) of about 15 s maximum. The lower arc energy of 0.5 kJ/mm corresponds to a calculated value of $t_{8/5}$ = 5 s. In practice, the impact toughness requirement and allowable arc energy will depend on the location of the weld, the stresses in the region of the weld and the minimum design temperature.

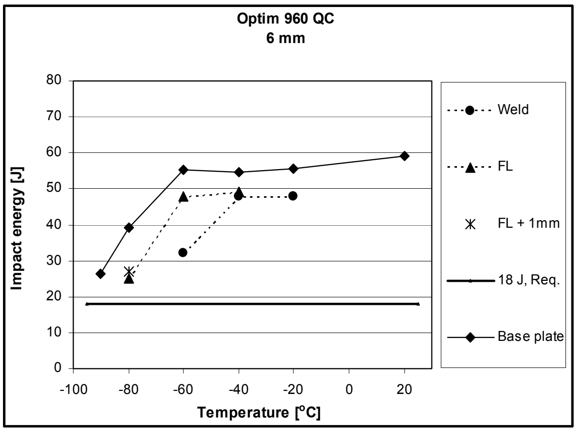

Fig. 10. Impact transition curves for the base plate and laser hybrid butt weld in 6 mm thick Optim 960 QC (transverse 5 x 10 mm specimens).

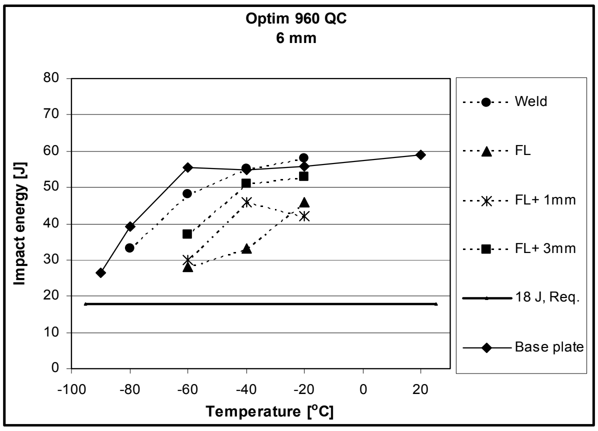

Fig. 11. Impact transition curves of the base plate and MAG welded butt joint (0.5 kJ/mm). 6 mm thick Optim 960 QC, transverse 5 x 10 mm specimens.

Figures 10 and 11 show that in the case of Optim 960 QC, the impact toughness of the laser hybrid and 0.5 kJ/mm MAG welded joints exceeded 18 J with 5 x 10 mm specimens to below –60 °C. (The 18 J requirement used here is based on 27 J for a full-thickness specimen and a correction factor of 2/3 to convert to a 5 x 10 mm specimen size). The impact toughness of the HAZ was better in the laser hybrid welded joint than in the MAG welded joint. This could be explained by the finer lath martensitic-bainitic microstructure found in the HAZ of the laser hybrid joint compared with the MAG welded joint, which is a consequence of the higher cooling rate in the laser hybrid weld. In the case of the MAG weld, the toughness of the FL/HAZ is limiting, whereas in the laser hybrid weld the weld metal toughness is limiting.

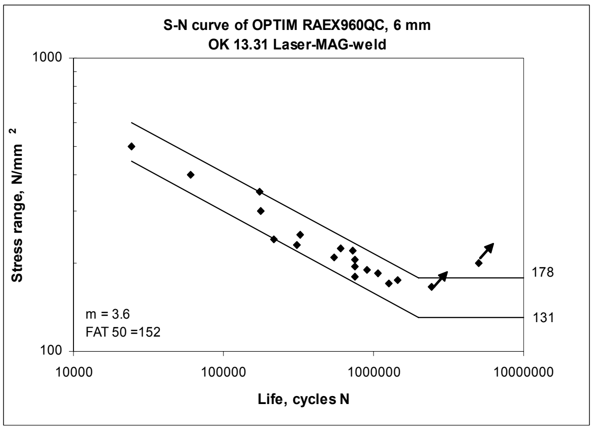

Fig. 12. S-N curves of the laser hybrid welded butt joint. FAT 5, 50 & 95 values: 178, 152 & 131 MPa. Best fit m = 3.6.

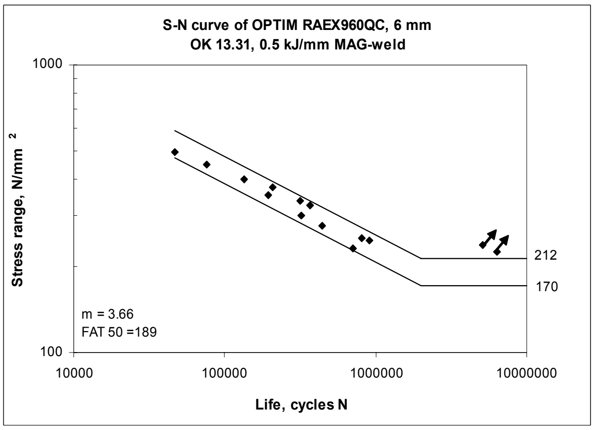

Fig. 13. S-N curves of the MAG welded butt joint. FAT 5, 50 & 95 values: 212, 189 & 170 MPa. Best fit m = 3.66.

The fatigue properties of the butt welds in Optim 960 QC were determined using constant stress amplitude testing under tensile loading with a stress ratio R = 0.1. The test results were

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plotted as S-N curves and fatigue classes calculated on the basis of 5, 50 and 95 % survival probabilities for two-sided 75 % confidence using the cracked specimens with $N \leq 2 * 10^6$ cycles, see Figures 12 and 13. The FAT 95 values, 131 and 170 MPa, are well above the normal design value for this type of weld, i.e. $\Delta\sigma = 80$ MPa. The higher scatter in the data from the laser hybrid weld compared to the MAG weld is presumably a consequence of its poorer quality.

8. SUMMARY AND CONCLUSIONS

Ultra high strength steels designated Optim 900 QC and Optim 960 QC have been developed as 3 - 6 mm thick plate for light-weight construction, especially for the structural members of mobile equipment. The steels are based on low carbon martensite with carbon content limited to 0.11 % at most.

In addition to high yield strengths of over 900 MPa, the steels exhibit very good impact toughness, typically around 200 J/cm^2 at –40 °C. The cold forming properties of the steels are also good due to their modified inclusions and low carbon and manganese contents.

MAG, laser and laser hybrid butt welding trials have shown that acceptable impact toughness properties are achieved in the weld using cooling times between 800 and 500°C of up to about 15 s. This means that 6 mm thick plates of Optim 900 QC or Optim 960 QC can be MAG welded using an arc energy of 0.8 kJ/mm. In this way, good impact toughness at -20°C can be obtained. Because of the very high strength levels and small plate thicknesses involved, the cross-weld tensile strength of butt welds is usually lower than that of the base plate, but it can be retained at base plate level by autogenous laser welding. Cross-weld tensile strength decreases as arc energy and cooling time increase. Laser-based welding processes allow the best combinations of strength and toughness to be obtained; however, softening is still found in the HAZ of hybrid laser-MAG butt welds. Due to the small thicknesses concerned and the low carbon content of the steel, preheating before welding is unnecessary. Indeed, the absence of preheat together with a low interpass temperature helps reduce the cooling time.

The strength and toughness required from a weld depends on its location, the stresses in the region of the weld and the minimum design temperature. When taken into account at the design stage, under-matching welded joints can often be fully acceptable. The development of design rules for dimensioning welded joints in thin high strength plate is an area of ongoing research.

Extensive industrial-scale trials have demonstrated that the developed steels have good flatness and surface quality. The material is suited to laser cutting and the fatigue properties of laser-cut parts have been shown to be good.

The fatigue strength of butt welds exceeds normal requirements, i.e. $\Delta\sigma = 80$ N/mm^2. The MAG welds showed better fatigue strengths and less scatter in the test results than the laser hybrid welds, presumably due to their higher quality class.

It has been shown that hot-dip galvanizing can be used for corrosion protection with no significant deterioration in the tensile properties of the steels. Best adherence of the zinc layer is achieved with short dipping times giving layer thicknesses less than 100 µm.

It has also been shown that pickling is not detrimental to the mechanical properties of the steels.

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