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Weldability and mechanical behaviour of induction assisted thick welds in high strength steel

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Abstract

High strength structural steels offer unique opportunities to manufacturers of welded structures due to the favourable combination of strength, formability and adequate weldability. However, for these materials, laser based welding processes (LB, LB-GMA) may raise some concerns regarding the excessive hardening and the associated problems in the as welded joints. In-line induction assisted welding may be a valid solution to obtain weld properties meeting most recognised requirements, while retaining the laser based process typical good productivity, in a fully automatic equipment.
Properties of induction assisted welds were extensively explored in a broad mechanical testing programme. While in-line induction heat treatment is usually found quite effective in smoothing the hardness peaks, its influence on other mechanical properties may be less favourable and therefore the induction additional energy must be carefully calibrated to avoid excessive heating.

Introduction

High strength structural steels (HSS) offer unique opportunities to designers of welded structures due to the favourable combination of strength, toughness, formability and adequate weldability. On the other side, steel structures manufacturers are in continuous search of more productivity in their welding processes to exploit the full economical potential of welded structure in HSSs. Laser based welding processes (Laser Beam (LBW), Laser Beam - Gas Metal Arc (LB-GMAW)) are very attractive, as they allow a joint to be welded in one pass, with no or fewer filler material, high welding speed and with low structure thermal distortion.
For a given steel, the joint metallurgical properties in both the weld metal (WM) and the heat affected zone (HAZ) are influenced mainly by the welding thermal cycle [1]. Unfortunately, laser based processes very often have quite low heat input compared to arc welding and therefore a severe thermal cycle is experienced by the steel being welded, with cooling rates that normally exceeds either the recommendations of steelmakers or the recognised good welding practice for ferritic structural steels [2]. Too low heat input induces severe hardening in both WM and HAZ, as consequence laser welds will have low ductility and increased risk of hydrogen induced cracking (HIC), due to the presence of large amount of hard untempered martensite. In-line (i.e. performed at the very same welding time) induction assisted welding may be a valid solution to obtain more easily weld properties meeting most recognised requirements, while retaining the laser based process typical good productivity in a fully automatic equipment. Typically, an inductor coil is placed near the welding thermal source, aligned with the joint path, and travelled together the welding head at fixed distance. The additional heat put into the workpiece is expected to promote intermediate rate cooling and therefore more favourable hardness figures.

Weldability backgrounds

Thick high strength (above 460 MPa yield strength) steels employed in welded structure construction are generally fine grained either quench and tempered (Q&T, consisting mainly of tempered martensite) or coming from a thermomechanical rolling route (TMCP, consisting mainly of very fine bainite), the latter normally being much less alloyed and therefore better weldable [1]. Welding of Q&T grades needs special care as a steep thermal cycle ($\Delta t_{800\text{-}500°C}$ cooling time lower than about 5s) may induce excessive hardening in both WM and HAZ and eventually lead to HIC and joint poor ductility. On the opposite, excessive heat input may induce HAZ softening and poor notch toughness properties [3]. For practical applications, recommended ranges for the $\Delta t_{800\text{-}500°C}$ parameter are given in various documents. Arc welding is generally found well practicable as the typical heat input figures and the multipass procedure turn out good joint properties, nevertheless preheating is normally adopted, unless on very thin products. Laser based welding is generally regarded as problematic, as one cannot rely on tempering, because single pass procedure is employed all times. The associated heat input is lower than arc welding and therefore the $\Delta t_{800\text{-}500°C}$ well less than 5s. WM is always quite alloyed, as matching filler wires are always richer than BM and considerable dilution invariably occur. Instead, TMCP grades are readily weldable by arc techniques and even by laser without concerns in HAZ due to the lower hardenability. No preheating is generally need. LB-GMA welding on TMCP grades may be more problematic, as filler wires are considerably richer and therefore the same WM hardenability of Q&T grades may be expected. TMCP grades are also quite sensible to excessive heat input, with deterioration of both the notch toughness properties and tensile strength [3]. TMCP steel are usually not intended for tempering/annealing after cooling below critical temperature, as the reheating may promote unfavourable coarsening of the strengthening precipitates.

The main purpose of the in-line induction heat treatment is to improve the metallurgical behaviour of the weld area, and therefore the joint mechanical properties, by altering the original welding thermal cycle by the addition of a further thermal source. The preheating and post heating approaches are set to have more time to cool, while the annealing (tempering) approach is intended to allow the metal to cool down below the critical martensite finish temperature (M_f) and then reheating at around 600 °C to temper martensite. The main difference compared to the traditional preheating practice (e.g. by flame or furnace) is that less surrounding material is heated. Another an area of uncertain is the effectiveness of the inductor over the full plate thickness, as the coil is placed on the welding side only and therefore the effect at the opposite weld root side is expected to be less intense as the plate thickness increases. Whatever the employed approach, the combination of the heat input and the BM preheating should always be kept inside the recommended working field for welding of structural steels (Fig.1). As can be seen, for laser based processes the risk of HIC or excessive HAZ hardening is important. The in—line induction heat treatment is usually found successful in smoothing the hardness peaks in as

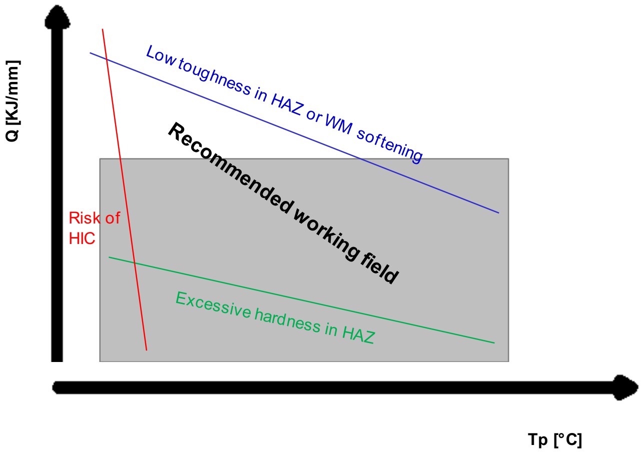

Fig.1. Qualitative welding workspace for thick high strength structural steels. Note the shaded area relevant to either LB or LB-GMA welding processes.

welded joints, the effect being particularly remarkable on Q&T steels, while welding on the TMCP grades usually do not turn out much hardening [4, 5]. Fatigue properties of welds are generally recognised to be nearly insensitive to the microstructure [6], but the induction heat treatment may vary to some extent the residual stress field (due to altered thermal field) and influence favourably the weld morphology [5]. Both are key factors in fatigue resistance (especially the latter)[6], although their effect is not expected to be of major impact.

Materials

Various steel grades were included in the experimental activity. S690QL steel was a Q&T grade with qualified toughness at -40 °C and the ability to offer its performance also on very thick plates. Main alloying elements were Cr (<1.5% in mass) and Mo (<0.6% in mass). S700MC and S500MC steels were TMCP grades with leaner composition compared to the Q&T grades, containing very little additions of microalloying elements such Nb, Mo, Ti, B depending of the required strength. The details on the material used are reported in Table 1.

Table.1. Steel grades properties and their welds requirements for matching joints, as for EN15614-1 standard [7], used in the experiments.

Steel grade	Thickness	Delivery condition	Welding process employed	Recommended $\Delta t_{800\text{-}500°C}$ range	Notch toughness	BM yield strength	Required weld tensile strength	Required max. hardness
	[mm]			[s]	[Joule]	[MPa]	[MPa]	[VHN]
S690QL	6	Q&T	CO_2 LBW, Yb:fibre LBW, LB-GMAW	5 ÷ 25	>27@-40 °C (KVT)	>690	>770	<450
S700MC	8	TMCP	CO_2 LBW	5 ÷ 15	>40@-20 °C (KVL)	>700	>750	<380
S500MC	6.8	TMCP	CO_2 LBW	5 ÷ 15	>40@-20 °C (KVL)	>500	>550	<380

Experimental activity

All laser welds were butt joints (300 x 350 mm coupons). In Table 2 is shown the matrix of the performed test welds with the main welding conditions. Laser welding without filler metal was performed either with CO_2 or Yb:fibre systems, differing mainly for the laser spot size, while LB-GMA welding was performed with filler material. The same steel was always welded with and without the induction treatment for testing the influence on the mechanical properties. Pre and post heating were also applied at the same time on selected specimens for assessing the maximum heating effect. The inductor coil design and the spacing from the welding thermal source and the workpiece varied with the actual laser system being employed from the various process developers.

Table.2. Matrix of the welding experiment performed on the various steel grades.

Steel grade	Original thickness	Welding Process	Induction heat treatment	Laser power	Welding travel speed	Gross Heat Input
	[mm]			[kW]	[m/min]	[kJ/mm]
S690QL	6	CO_2, Yb:fibre LBW	None (as welded), Pre, Post, Annealing, Pre+postheating	3.0 ÷ 3.5(CO_2)	1.0	0.21
S500MC	6.8	CO_2, Yb:fibre LBW	None (as welded), Pre, Post, Annealing, Pre+postheating	3.0 ÷ 3.5(CO_2)	1.0	0.21
S690QL	6	LB - GMAW	None (as welded), pre, Postheating	6.0	1.5	0.58
S500MC	6.8	LB - GMAW	None (as welded), Postheating	6.0	1.0	1.02
S700MC	8	CO_2 LBW	None (as welded), Pre, Postheating	12.0	4.0	0.18

Qualification process intended to explore the ability of induction assisted welds to match BM minimum mechanical properties, therefore tensile and notch toughness testing (Charpy-V) were carried out. Widely recognised standards were followed during the testing session. Transverse tensile testing met EN 895 [8] standard. Testing was made at room temperature on a servohydraulic rig. For notch toughness testing, EN 875 standard [9] was adopted, by using through thickness specimens with reduced height (5 or 7.5x10x55 mm), depending the specific steel grade being tested. Sampling position was immediately below the upper surface, with notch located by suitable macroetching. Testing for toughness of BM (untreated), WM centreline (VWT0/0 specimen), HAZ near (1 mm) fusion line (VHT1/0 specimen) was done by mean of 3 tests for each position and welding condition. Actual measured values were normalised for comparing to normal 10x10mm Charpy-V specimens. Testing temperature was always -40 °C. Butt welds were tested for fatigue resistance in tension with axial sinusoidal load, load ratio R=0.1, in air, at room temperature. Standard structural detail approach was followed, S-N data were shown on log – log diagrams together with the mean line regression (50% probability of failure). In Fig.2 is reported the fatigue specimen shape.

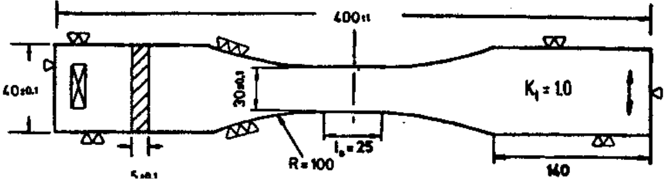

Fig.2. Specimen for fatigue testing of laser welds.

Experimental results

Tensile strength of induction assisted welds

Tensile tests were carried out on S700MC LB butt welds 8 mm thick (the steel grade more concerning about weld area softening). Two specimens per condition were cut out from the welded samples (total 18 tests), with weld reinforcement untouched. Specimen parallel length was 100 mm, width at parallel section was 25 mm. Untreated, preheated and postheated items were included in the investigation. In Fig. 3 is reported a resume of the recorded results. From a qualification point of view, all samples met minimum S700 grade requirements ('matching' tensile strength), with tensile strength always exceeding 750 MPa (actual values ranged from 805 to 892 MPa). It is worth to note that BM itself had TS much higher than the minimum requirements, so to better evaluate the effect on WM softening, a comparison with the actual BM tensile strength should be made. Fracture occurred either in parent metal or weld area. It was evident that "heavy" induction heat treatment (preheating with more than 17.5 kW, postheating with more than 6kW) changed the basic overmatched condition (fracture in

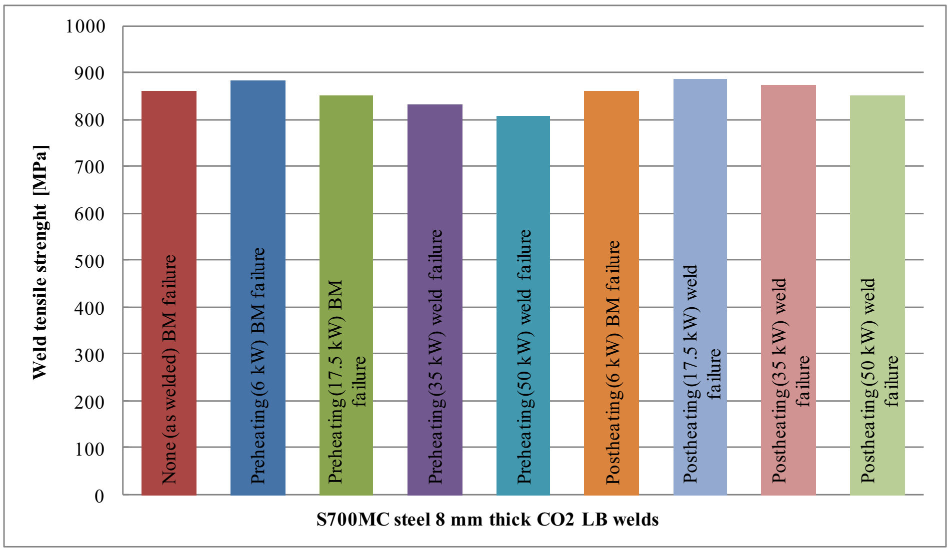

Fig.3. Laser weld tensile testing results for S700MC steel 8mm thick.

BM, away from the weld) to the less desirable undermatched condition (failure in the WM). In fact, tensile strength was optimal in either the untreated or "soft" induction treated condition.

Notch toughness (Charpy-V) of induction assisted welds

It was learned from the tests performed that all welds met in the not treated conditions minimum toughness requirements at the relevant testing temperature (e.g. 27J at -40°C for S690 QL). Besides, there was evidence that the induction heat treatment (pre, post or annealing) may lead to toughness deterioration compared to the untreated condition, depending on the specific grade, the notch position and the kind of heat treatment. For example, annealing (tempering) was very effective in raising adsorbed energy on the investigated Q&T grade S690, while preheating was not. Such broad trends for the investigated grades and the results are resumed below in Table 3 and Table 4 for HAZ and WM respectively of laser beam welds only.

Table 3 – Measured notch toughness and broad trends for HAZ (LBW) notch toughness (compared to the untreated condition).

Steel grade	BM notch toughness	No induction	Preheating	Postheating	Annealing	Pre+ Postheating
	[J]	[J]	[J]	[J]	[J]	[J]
S690QL	83	40 ÷ 82	30↓	43↔	75↑	74↑
S500MC*	188	265 ÷ 192	232↔	196↔	192↔	18↓
S700MC	43	35	42 ÷ 102↑	34 ÷ 42↔	-	-

↑: better; ↔: no significant effect; ↓: worse. Mean of 3 specimens normalised at 10 mm equivalent Charpy-V size. *Fracture path deviation often occurred.

Table 4 – Measured notch toughness and broad trends for WM (LBW) notch toughness (compared to the untreated condition).

Steel grade	BM notch toughness	No induction	Preheating	Postheating	Annealing	Pre+ Postheating
	[J]	[J]	[J]	[J]	[J]	[J]
S690QL	83	86 ÷ 106	51↓	56↓	98↔	32↓
S500MC*	188	231 ÷ 230	174↔	218↔	220↔	36↓
S700MC	43	72	23 ÷ 33↓	27 ÷ 35↓	-	-

↑: better; ↔: no significant effect; ↓: worse. Mean of 3 specimens normalised at 10 mm equivalent Charpy-V size. *Fracture path deviation often occurred.

As general trend, more additional heat put into the weld induced higher detrimental effect, eventually very heavy induction heat treatment could be so unfavourable (e.g. intense pre+postheating) to miss even minimum toughness requirements. The metallurgical explanation of such circumstance rely on the HAZ extension (Fig. 4) and the associated grain coarsening and polygonal microstructure promoted by the excessive heating.

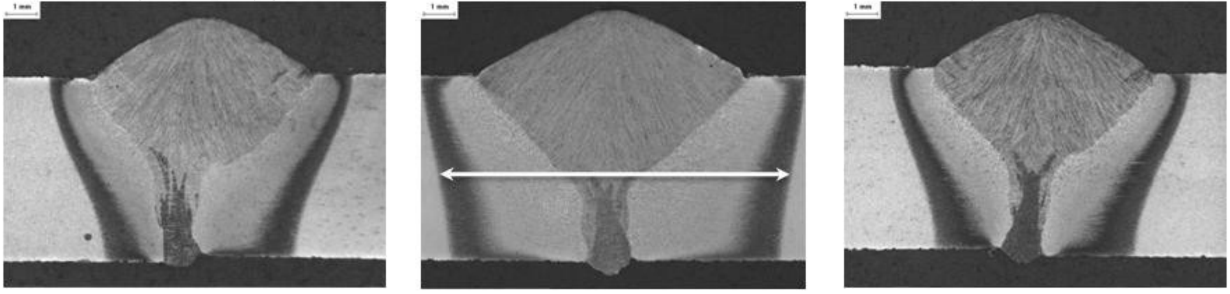

Fig.4. The same welding condition untreated and assisted with induction pre or postheating (from left to right respectively). The HAZ was very widened (arrowed in the photo) by the additional heat, with expectable grain coarsening and therefore less favourable notch toughness properties. Note the WM reinforcement toe nearly unchanged. All were LB-GMA welds on S690QL steel.

Fatigue strength of induction assisted welds

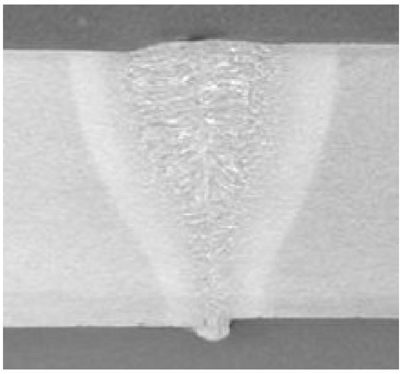

Fig.5. Macrosection of LB weld on S500MC steel 6.8 mm thick. Note the flat reinforcement cap low susceptible to be altered by the additional heating.

Measurement of laser welds fatigue strength and the assessment of the effect of the induction heat treatment was made for S690QL, 6 mm thick (LBW), and S700MC 4 mm thick (both LBW and LB-GMAW) in untreated and with induction heat treatment. At least six specimens per condition were cut out from the welded samples and tested. Broken sections evidenced sound WM. In broken specimens, fracture initiated (not surprisingly) at the upper reinforcement toe for S700MC welds, at either upper or lower reinforcement toe for S690QL welds. The results as whole were good for the respective categories (LBW, LB-GMAW), as no detrimental imperfections were revealed. Clearly, the LB welds had better fatigue resistance due to the very smooth profile. In that, the more notched LB-GMA welds had fatigue strength comparable to traditional arc welds. Regarding the effect of the induction heat treatment, for LB welds on S690QL could not be found any correlation between the induction heat treatment being experienced and the fatigue strength of the relevant weld, as the induction heat treatment couldn't influence the WM shape (that is, by far, the strongest factor influencing the fatigue resistance). In fact, checking the very little WM reinforcement (Fig.5), one hardly could expect any difference between the various samples. In Fig. 6 the S-N diagram for LB welds on S690QL steel is reported. For LB-GMA welds the differences were so narrow that any design credit couldn't be recommended for specific welding condition(s), with induction heat treatment or not. Again, quite no variations were found in WM toe morphology (Fig.4). Moreover, as in Laser-GMA hybrid welding the WM shape can be strongly affected by several process factors (e.g. wire feed rate), it is unlikely that induction heat treatment could influence the weld geometry as much and with repeatability. In Fig. 7 the S-N diagram for LB-GMA welds is reported.

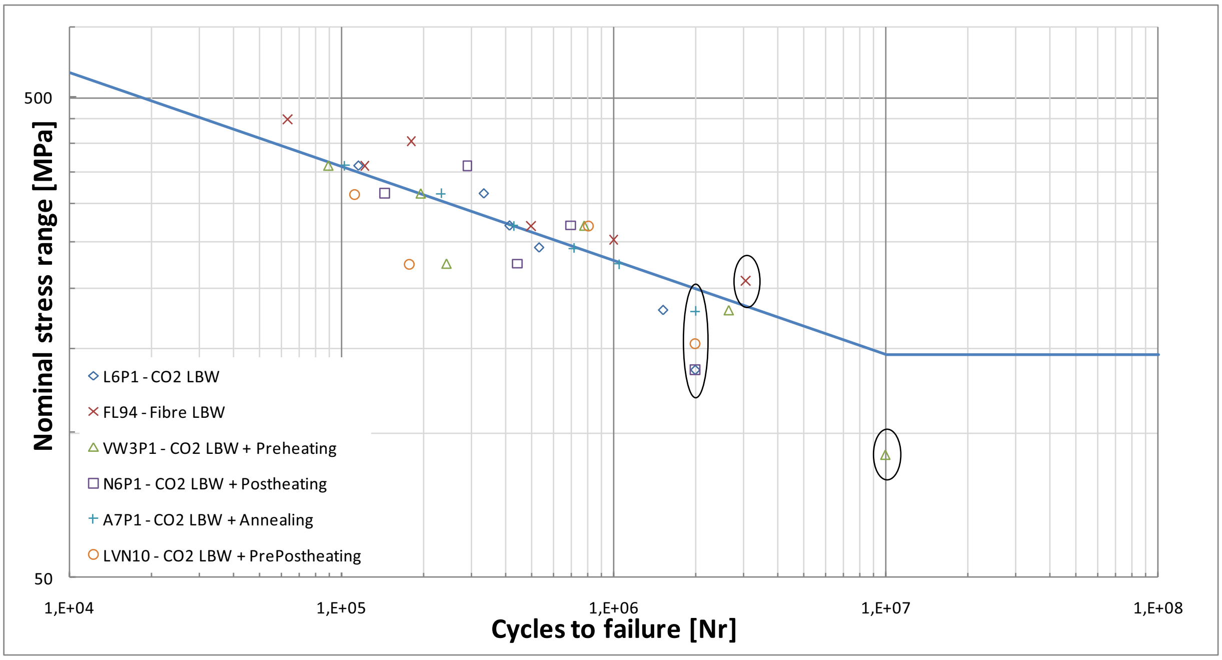

Fig.6. Sr-N fatigue diagram for induction assisted LB welds on S690QL steel (run-out tests circled).

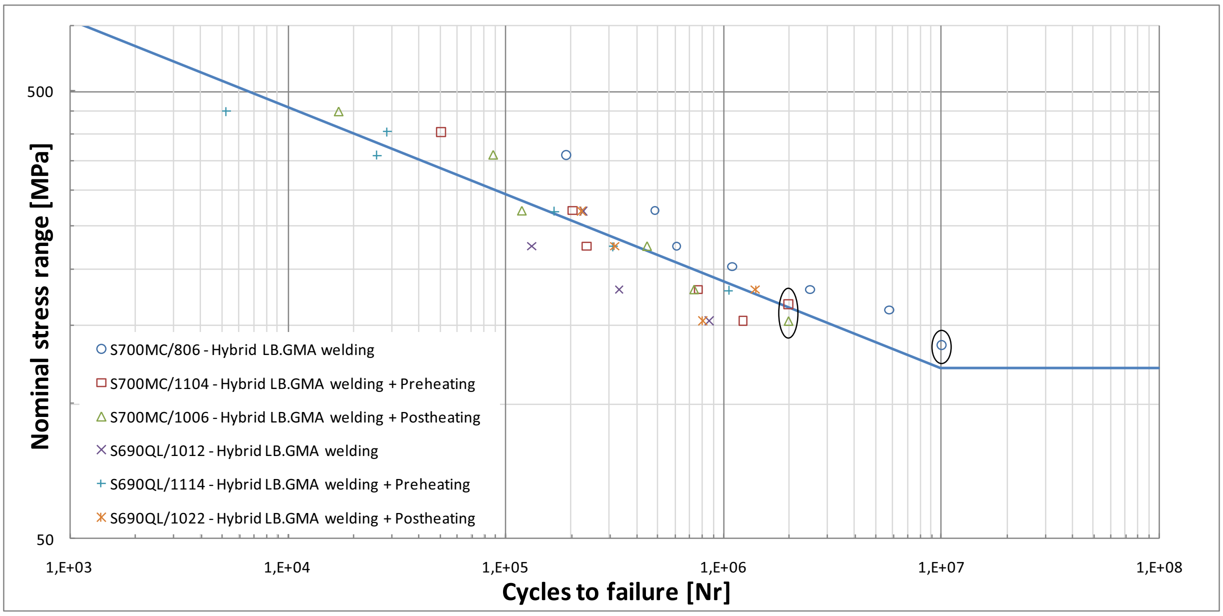

Fig.7. Sr-N fatigue diagram for induction assisted LB-GMA welds (run-out tests circled).

Conclusions

Induction assisted laser welding is a viable system to overcome hardness requirements limitations that comes from the too low heat input intrinsic of the laser based processes (LBW, LB-GMAW) applied on structural ferritic steels. Although the in-line induction heat treatment was found generally effective in smoothing the hardness peaks on HSS, especially the more alloyed Q&T grades, excessive additional heat put into the weld may lead to mechanical properties deterioration with respect to the untreated condition. A broad range of laser welds made on S690QL, S700MC, S500MC structural steel grades (thickness range 6÷8 mm) with and without the induction assistance were investigated by transverse tensile, notch toughness (Charpy-V) and fatigue testing. It was found that fatigue properties were nearly unaffected from the induction heat treatment, as the WM shape was hardly altered. Too additional heat led to WM softening on S700MC TMCP grade laser welds, changing the failure mode from the ideal BM (overmatching) to the undesirable fracture in WM (undermatching). Regarding notch toughness properties, best results were achieved in the untreated condition (or induction tempered for Q&T grade only), while either pre or postheating promoted toughness deterioration on most grades due to the grain coarsening ant the unfavourable microstructure. It was concluded that the additional energy must be carefully calibrated to avoid excessive heating and the welding procedure including the induction assisting must be qualified for each application by mechanical testing.

Acknowledgements

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