Welding evaluation on high hardness armor steel

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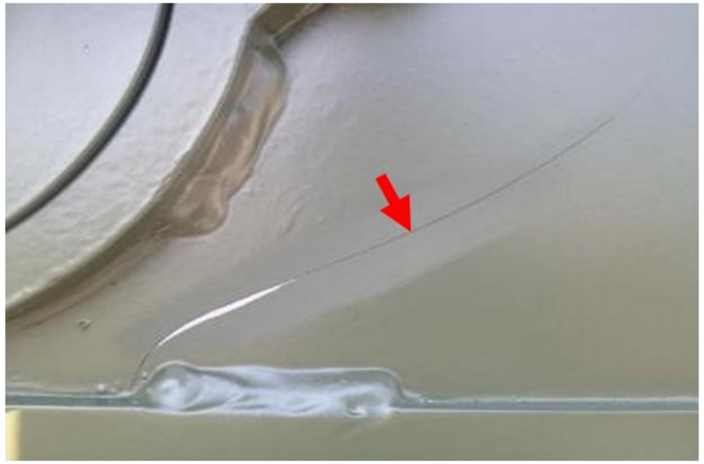
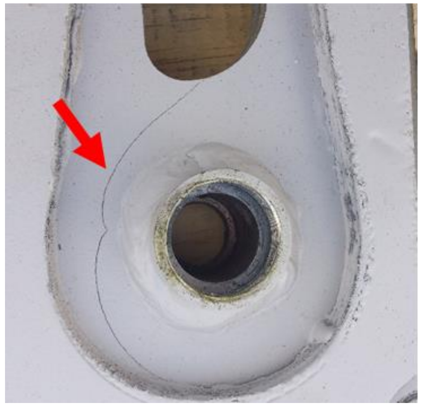
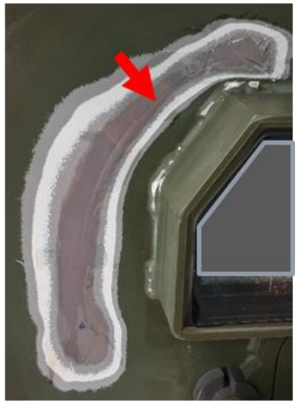
Background and rationale

- Scope of the work is estimate feasibility of LBW and MIG welding techniques for UHH grade armor steels.
- UHH is Ultra High Hardness acronym, applicable for steels 570-650HB (57-61HRC) and carbon content max 0.55% with Mn, Cr, Mo, B, Ni alloyants.
- Typical CE (IIW) for UHH steels is 0.8-1.1,.
- Welding of high CE steels is challenging process, because of delayed cracking and formation of very hard untempered martensite zone in HAZ.
- MIG process, applied on UHH steel, aimed to learn closer potential problems, and to find applicable ways to prevent it. Use of austenitic consumables is known approach to join difficult-to-weld steels. Less hard armor steels traditionally welded with ferritic electrodes.
- LBW is attractive procedure due to narrower HAZ, compare to conventional MIG-based process, that expected to be ballistic advantage. High energy input and rapid melting/solidification acts, expected to beneficial contribution to mitigate hydrogen damage.
- UHH armor steels M600 and BA-UHH, manufactured by Industeel AM (France) and Bisalloy (Australia) companies, were chosen for investigation. Choice of M600 governed by highest CE value, among commercially available UHH steels. M600 represented ‘hard way’ case, because of High CE and expected to exhibit possible problems and challenges.

Alkemade, S.J., 2015 unpublished research







Hydrogen damage - metallurgical threat for mechanical reliability

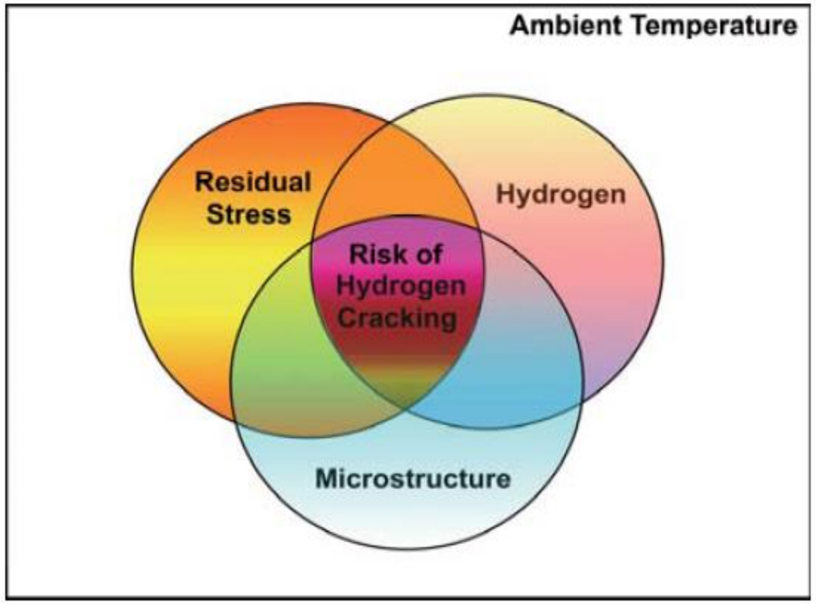


Fig. 1 An illustration of the three essential conditions occurring simultaneously to cause HAC

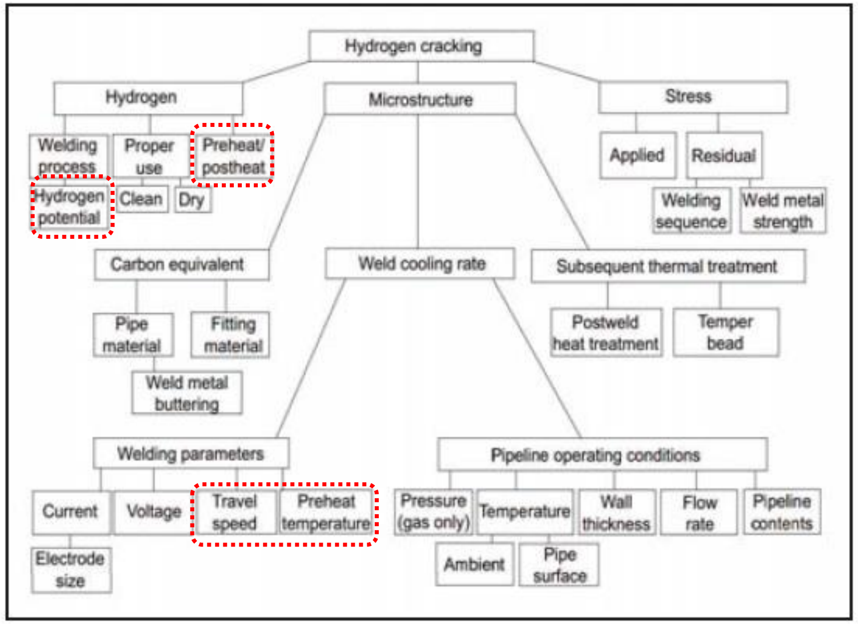


Fig. 4 Schematic representation of various factors influencing HAC [16]

Source G.K Padhy, Diffusible Hydrogen in steel weldments, Transactions of JWRI, vol.4 [illegible] /publication/trans-jwri/pdf/421-07.pdf

Experimental

1. Visual examination performed in according with guidance lines of AWS D1.1 and ASNT NDT HBk.
2. Micro hardness testing was performed in according with ASTM E384
3. HRC hardness test by ASTM E18
4. Vickers hardness test ASTM E92
5. Metallographic specimens were prepared according to ASTM E3, Metallographic etching ASTM E 407
6. Conversion of hardness between Vickers (HV), Rockwell (HRC) and Brinnel (HB) scales applied as per ASTM E140.
7. Elemental analysis by XRF analysis guided by ASTM E1621 – 13. SEM EDS analysis by ASTM E1508
8. Grain size on microstructures accessed with ASTM E112

Referred sources:

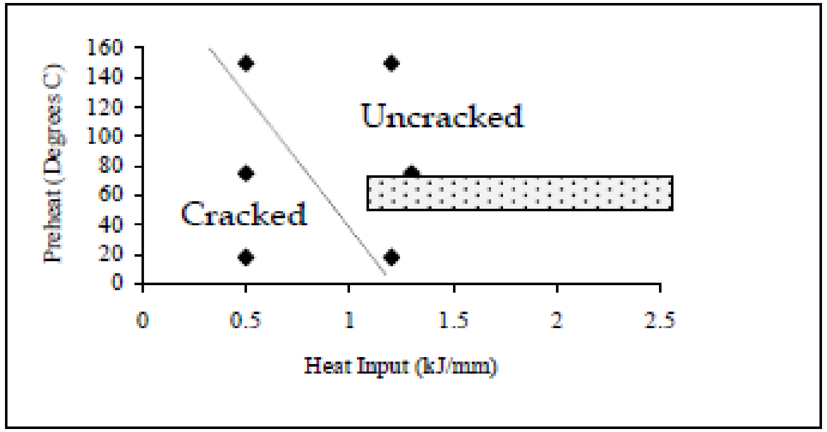
ISO 13919-2 – Electron and laser-beam welded joints – Requirements and recommendations on quality levels for imperfections.

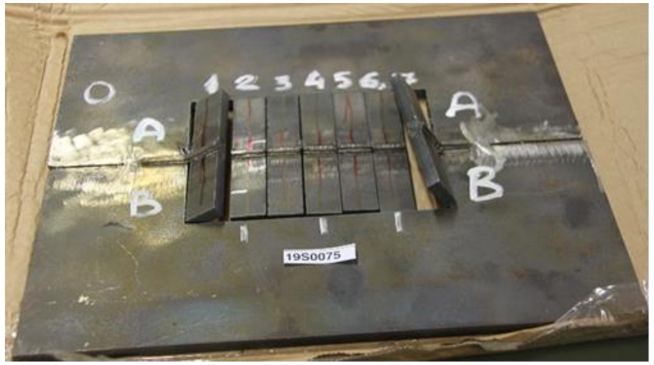
AWS D1.1 Structural Welding Code –Steel, Reference Manual

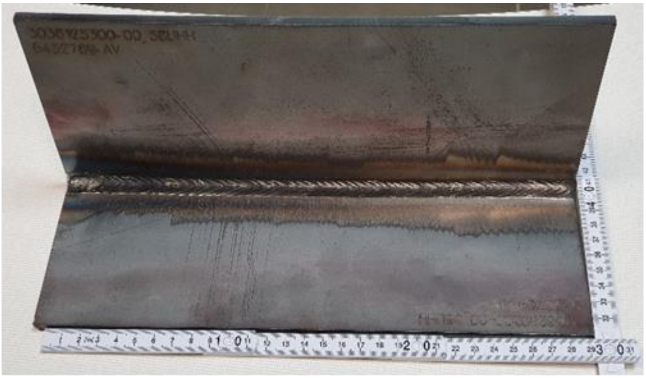
ASNT Handbook Nondestructive Testing Handbook, Third Edition: Volume 9, Visual Testing

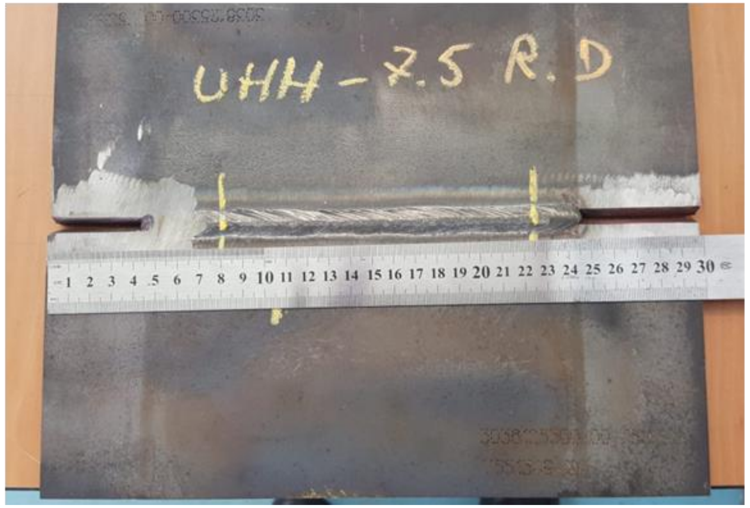
MIG welding

1. Austenitic wire used for welding trials. No preheat applied for welding of plates below 10 mm thickness. Heat input 0.8 kJ/mm
2. Well controlled procedure provides sound welding and crack free joints.
3. Conventional bend test for welded high strength steel always caused fracture within weld metal.
4. Weld samples successfully passed RD test

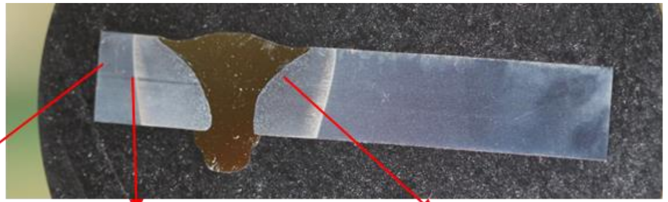


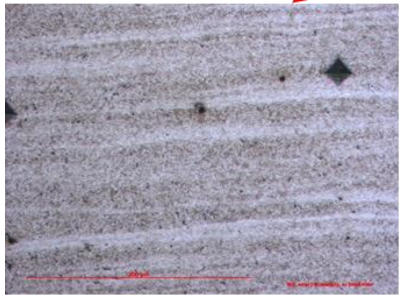




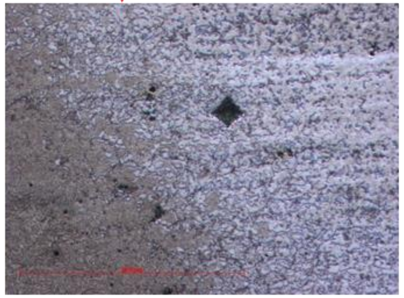


Microstructure and hardness profile

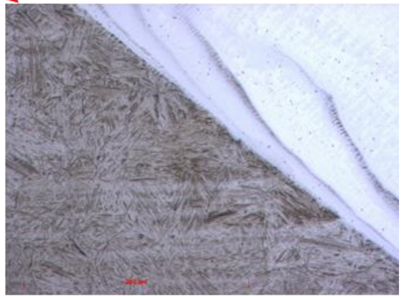




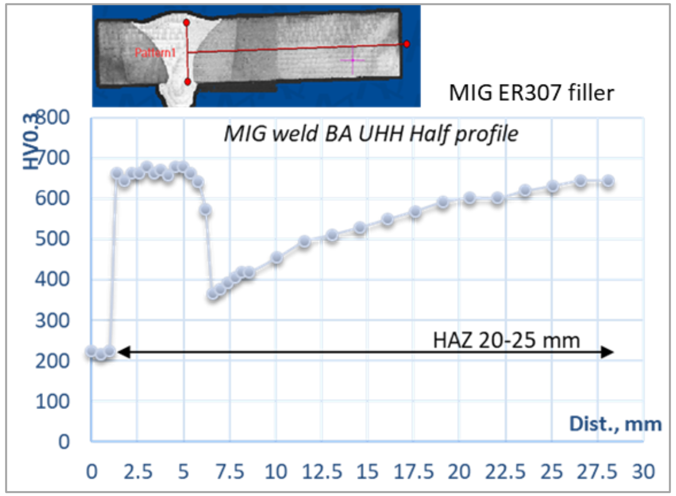
TM microstructure of unaffected steel



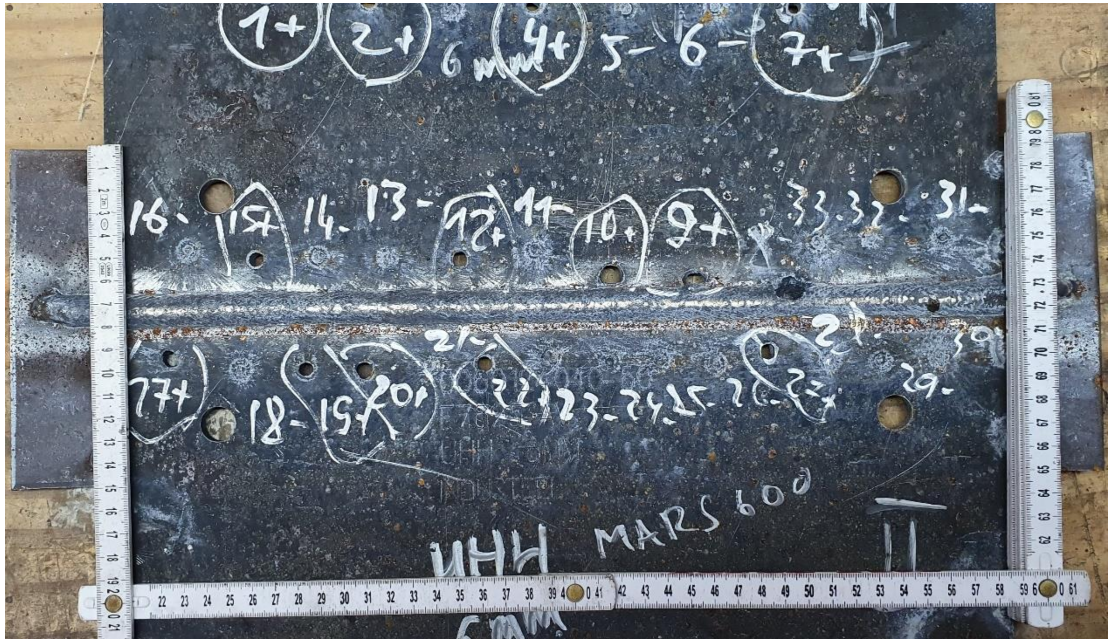
White line area – transition from GP to TM



Dominant M microstructure close to A filler zone

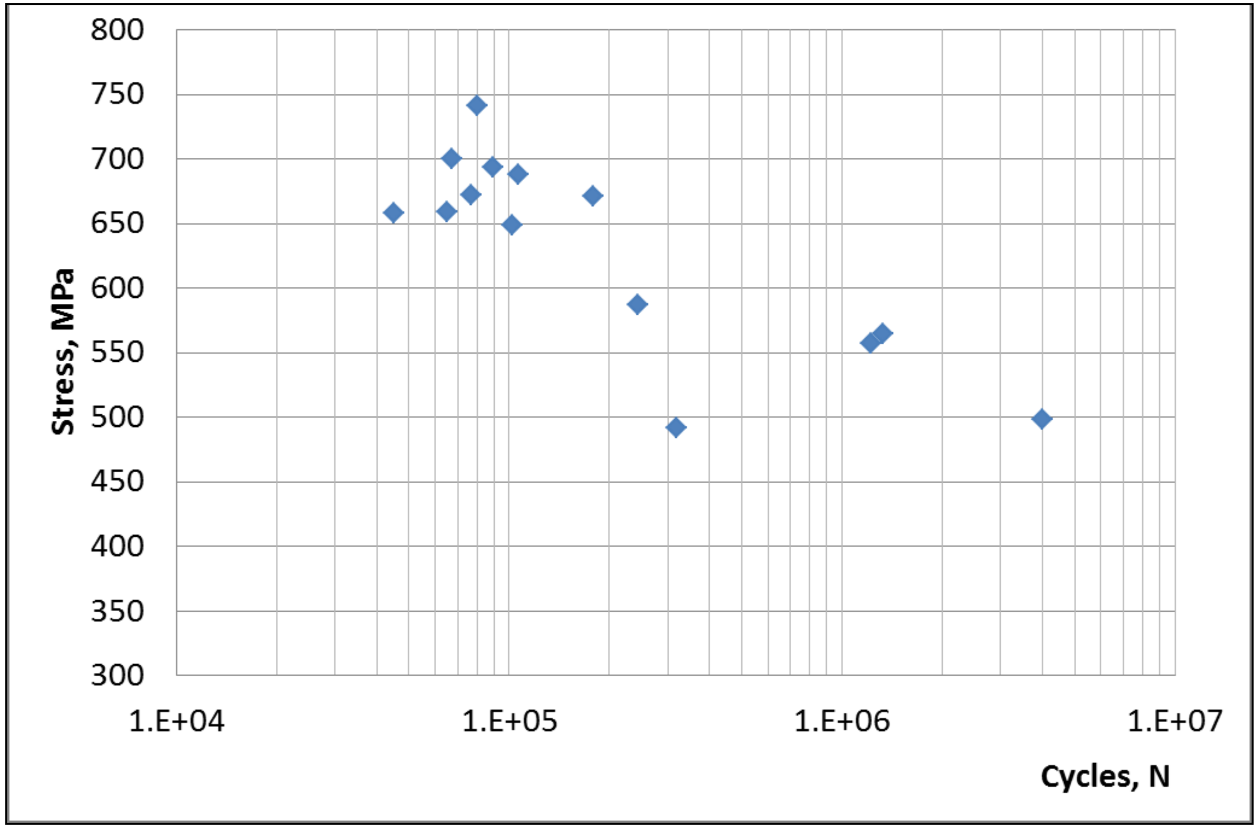


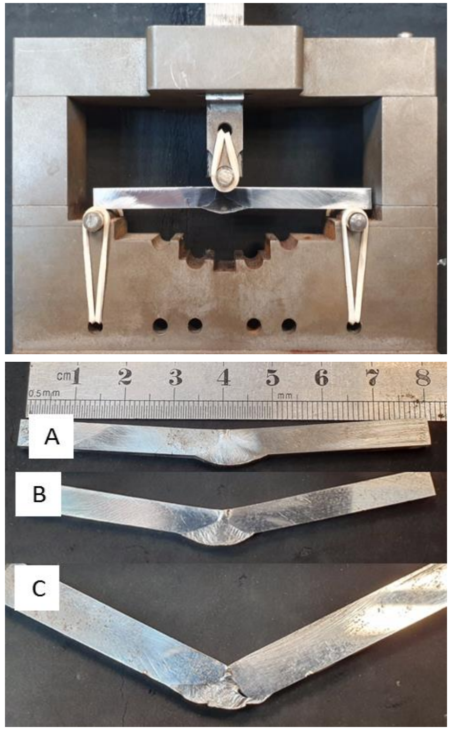
1. High hardness 'tooth' is very close to unaffected steel core. Width of soft part of HAZ is 15 mm in average. Hard range is about of 3-4 mm.
2. Series of weld samples were found free from defects, based on limited statistic of dozens specimens



(T)M- (tempered) martensite, B – bainite, (G)P- (granular) pearlite, A - austenite

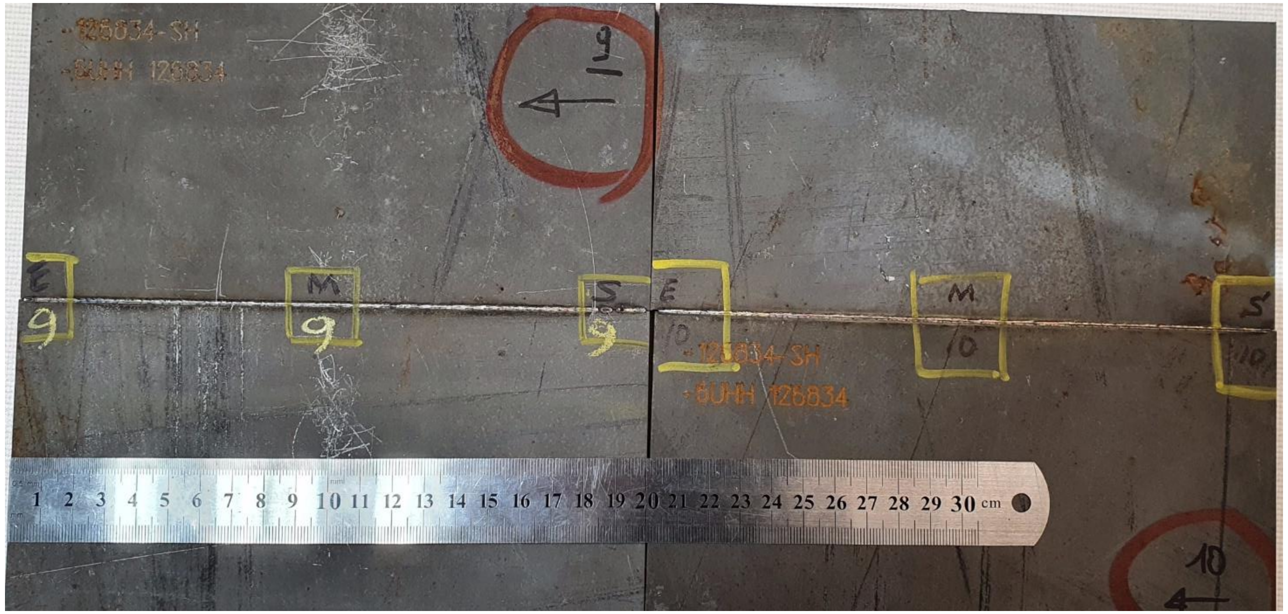
Fatigue behavior





Fatigue is most complex mechanical test for weldments, because of its sensitivity for any weld induced imperfections and metallurgical defects.
Fatigue strength for flawless UHH weld specimens steel is close to fatigue limit of filler alloy ER307 (AWS A5.9).
Fatigue limit as 500-600 MPa makes possible to consider implementation of UHH welding in mechanical design.

Early welding trials

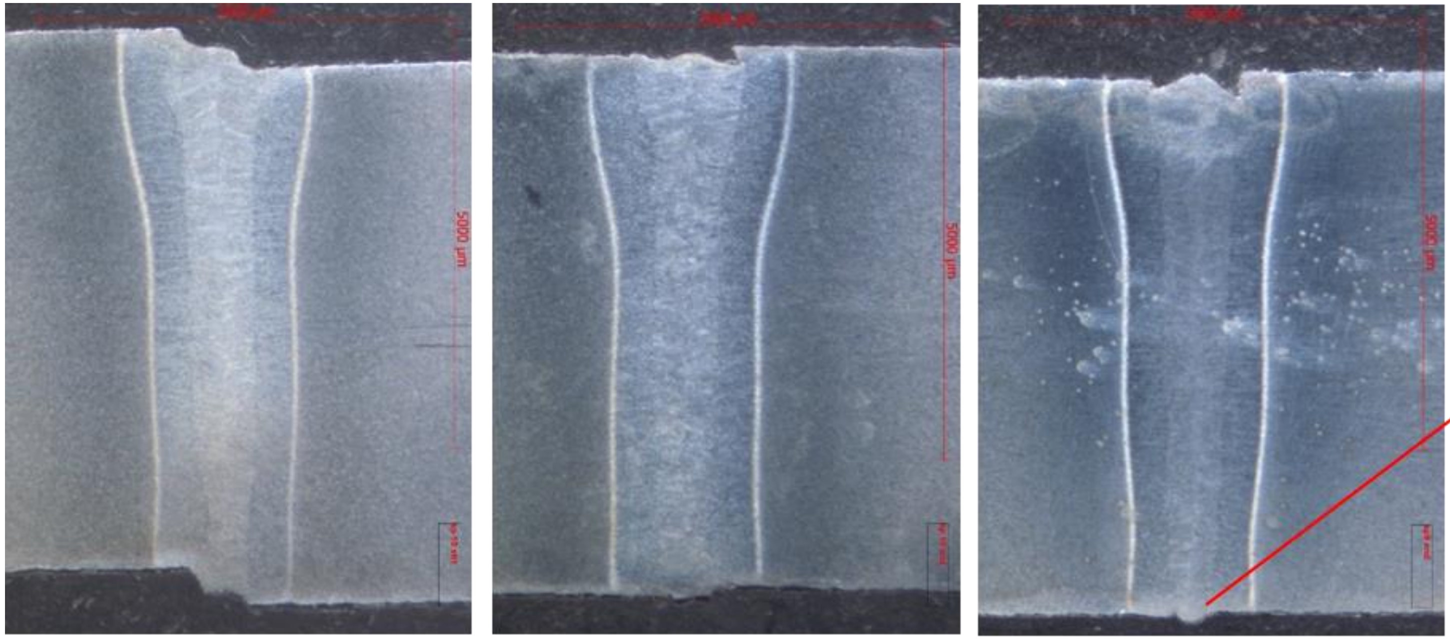


Laser beam welding is very attractive for welding CE steels and very susceptible for formation of untempered M-phase because of extremely high solidification and cooling rates.

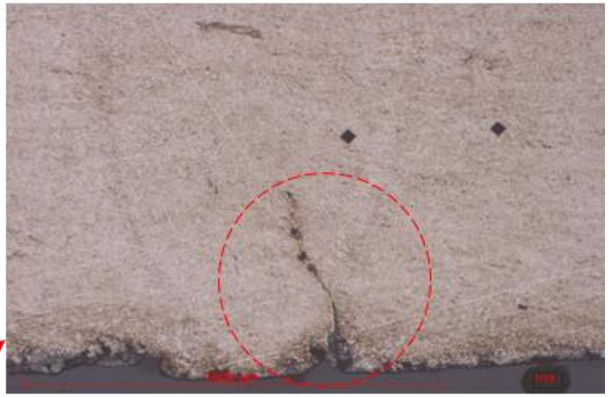
Primary welding trials performed with procedure parameters, adopted in serial production of low carbon constructional steel.

Macro appearance of weld seams is acceptable in terms of visual inspection criteria (AWS/ISO specs).

Defects observed on first steps of the work - filler free LBW



Misalignment of plates

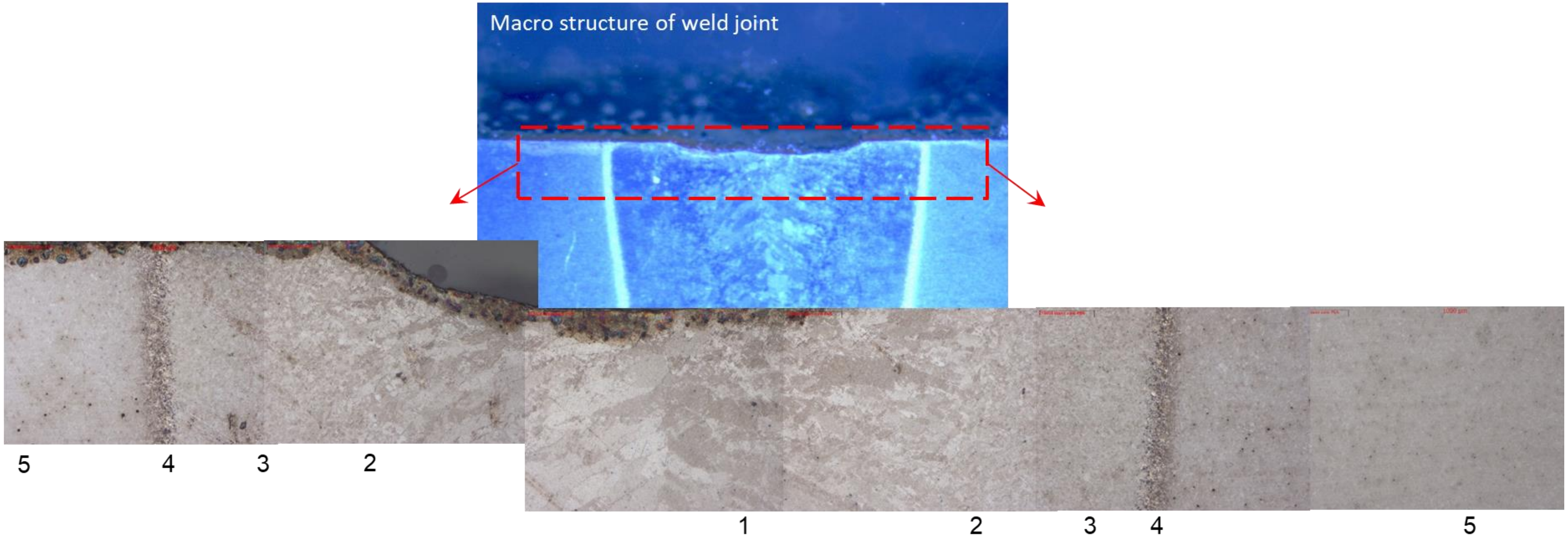


Root crack-like discontinuity

First trial tests revealed:

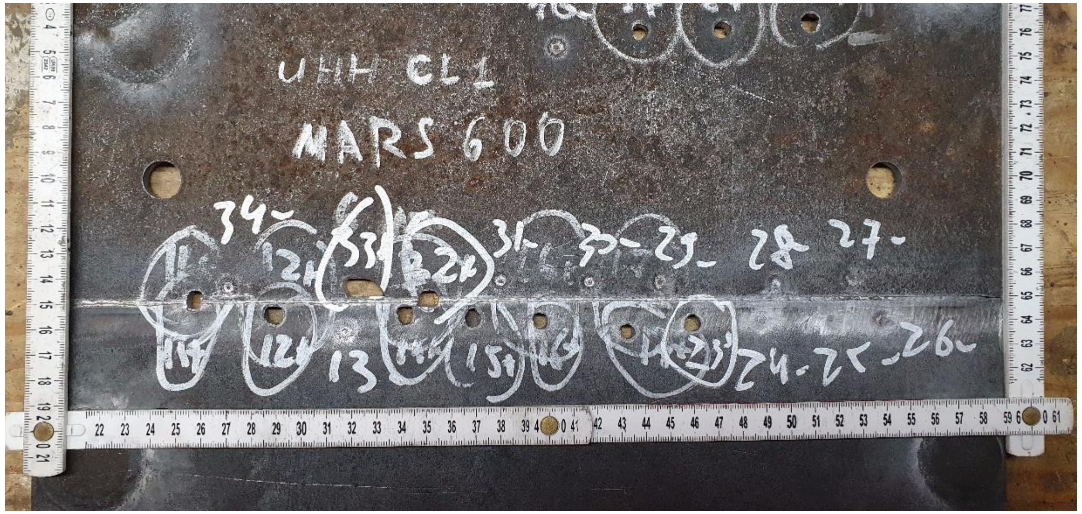
1. Poor setup configuration, caused to misalignment problem (ref.507 per ISO 6520-1)
2. Discontinuity in root of weld metal, fusion defect and hot microcrack.
3. Correction of setup and tuning of process parameters resulted in flawless welds, beside of sagging defect.
4. Use of filler wire eliminated sagging effect

Microstructural descriptors



1 – fusion zone, columnar grains, ~700 HV
2 – transition from Coarse grains recrystallized zone to (1) to Fine grains recrystallized zone (3).
3 - fine grains recrystallized zone, high hardness 700HV
4 – white line, narrow transition zone from high hardness martensitic phase to tempered one. Hardness fall down from 700 to 400HV (min value within HAZ)
5 – portion of steel, less affected by weld heat

Hardness profile – mid thickness section



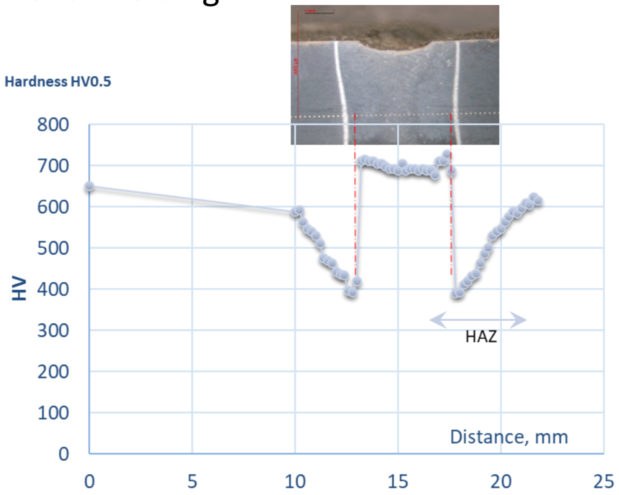
Laser beam produced very high hardness weld metal zone, 670-700HV, due to untempered martensite within fusion and proximal recrystallized layer. High hardness remains constant within 'white lines' range, which was heated beyond A_3 temperatures. This specific effect that does not exist for conventional weld, like MIG, reported above.

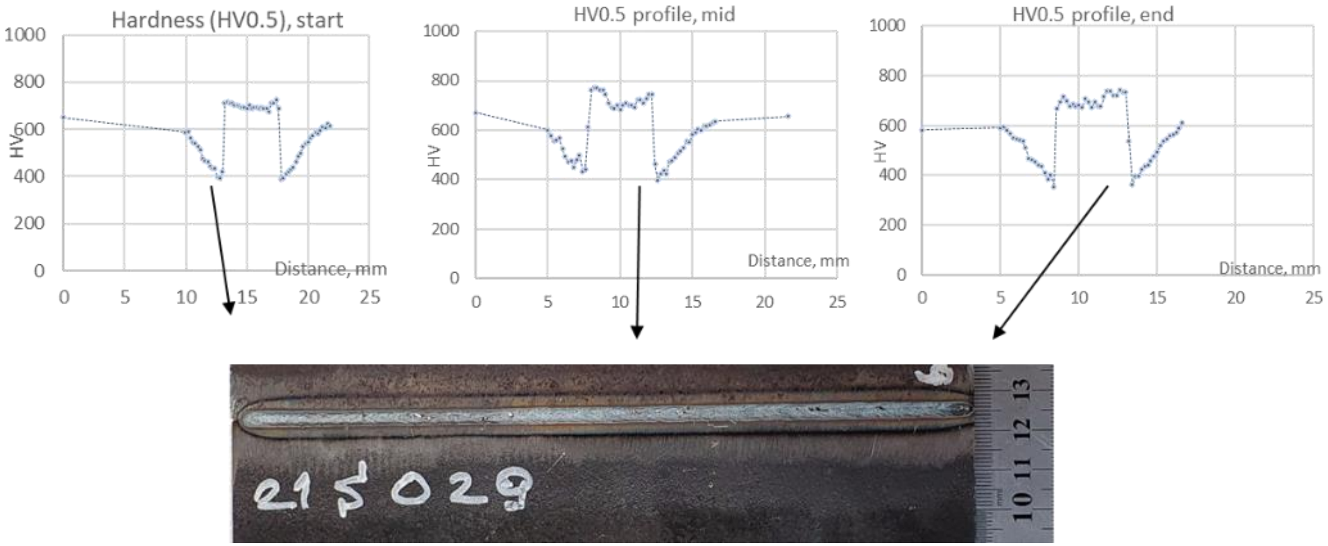
White line is very narrow zones, where hardness dropped from Max to Min. i.e. here is structural change from untempered martensite to tempered phase, 400HV or less.

Outside of white lines, hardness recovered to intact steel hardness, within the distance of 3.5-5 mm.

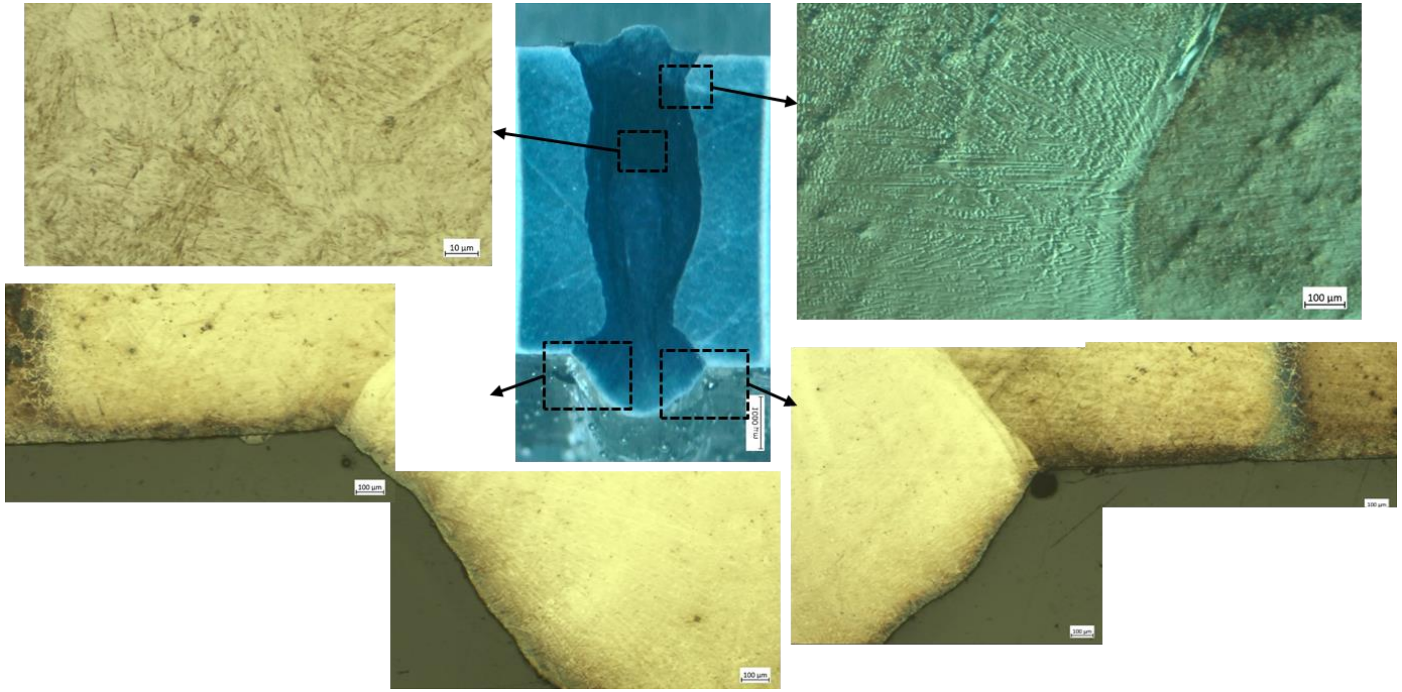
Overall width of HAZ joint was found below 8-10 mm, while hard plateau is about of 4 mm.

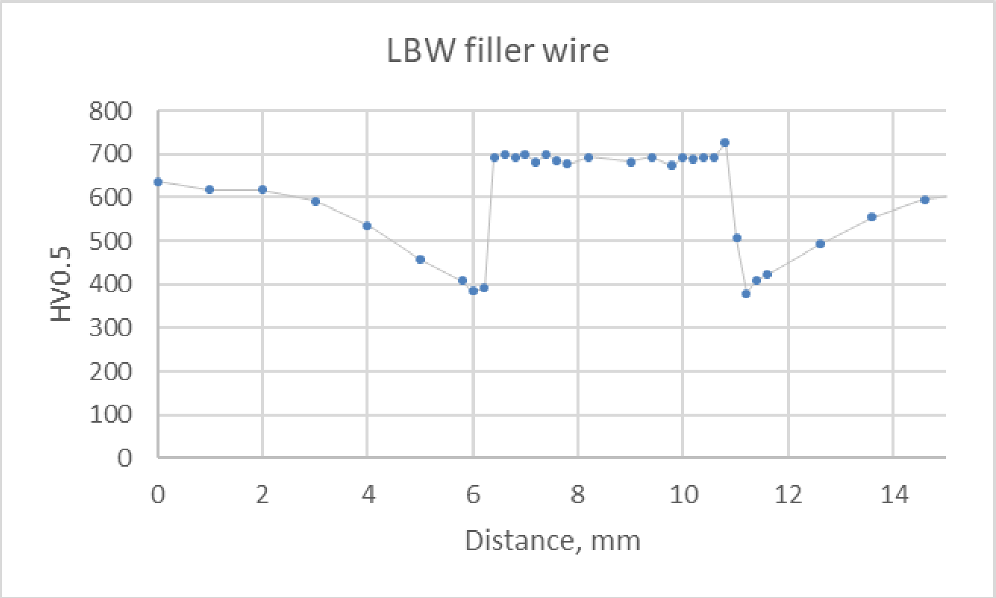
Very narrow HAZ and hard weld metal zone provided higher ballistic efficiency compare to conventional welding





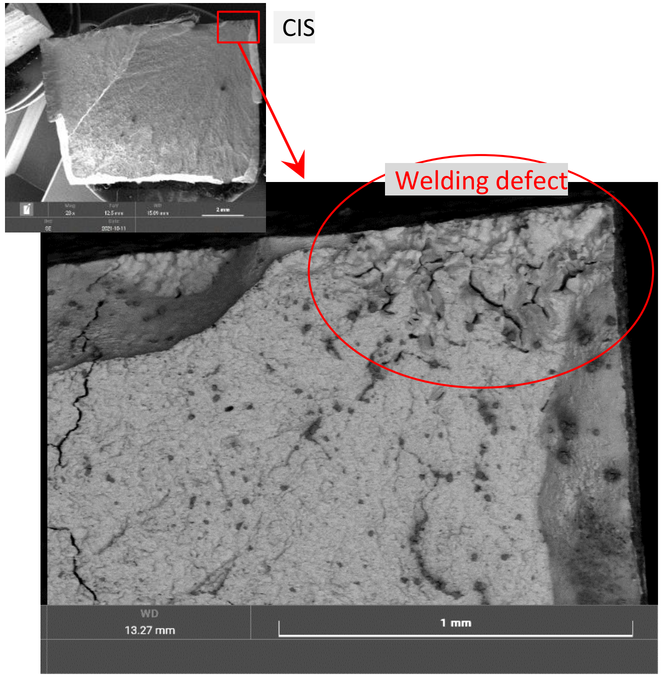
Wire assisted LBW

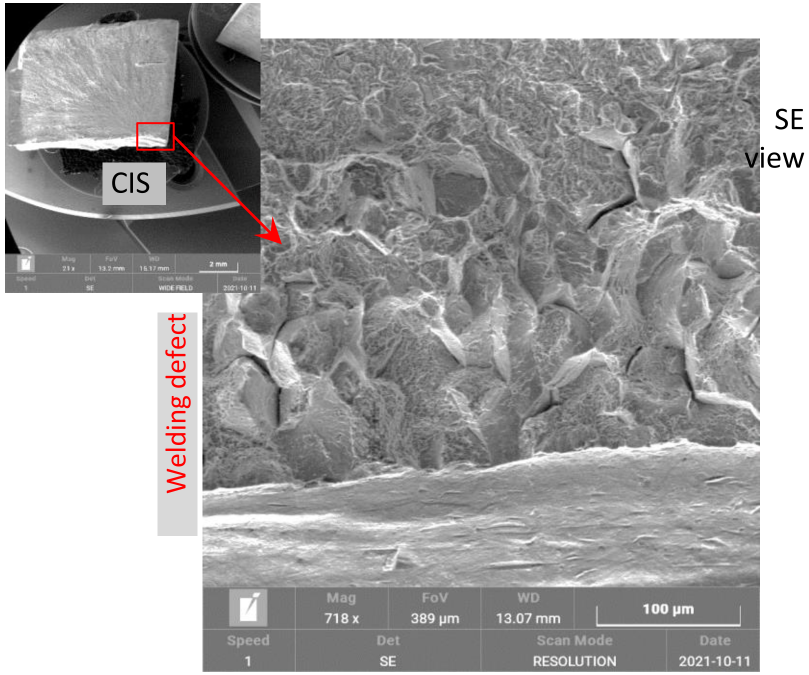




Addition of filler wire enhanced significantly weld geometry. Hardness profile remained similar to filler free welding, but high hardness plateau decreased slightly. Use of filler wire has no effect on HAZ size.

Tensile strength and impact (Charpy) test



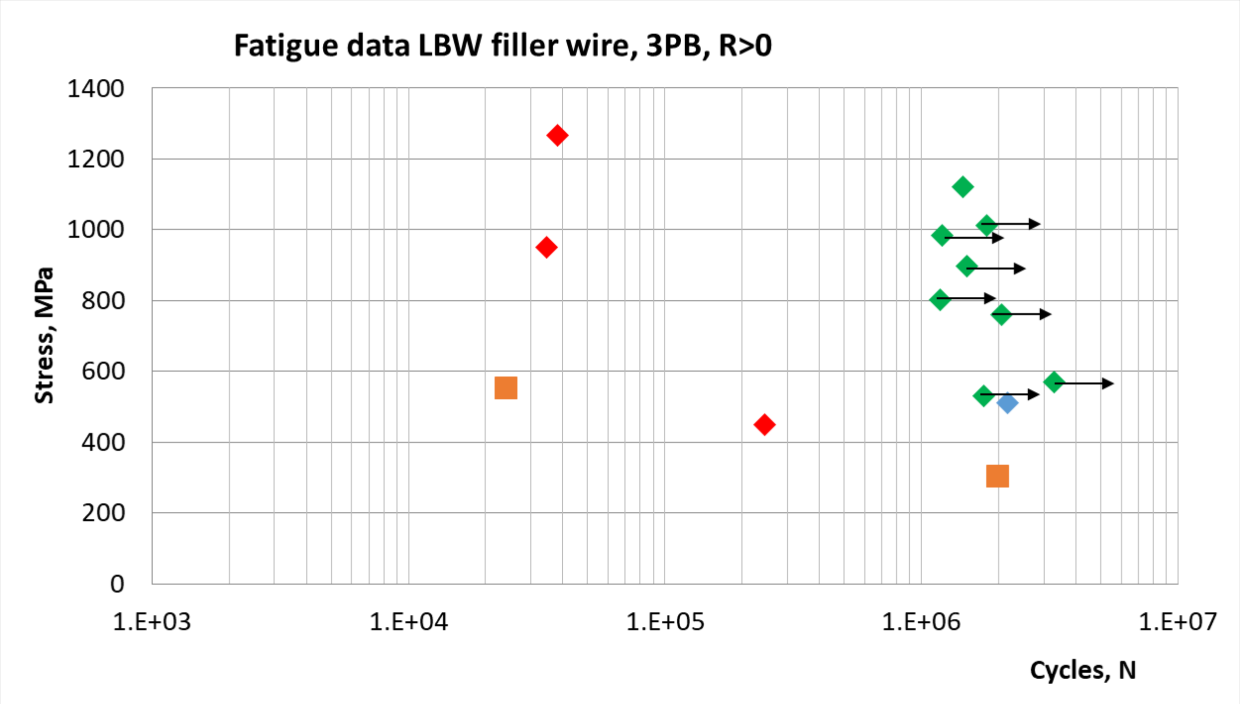


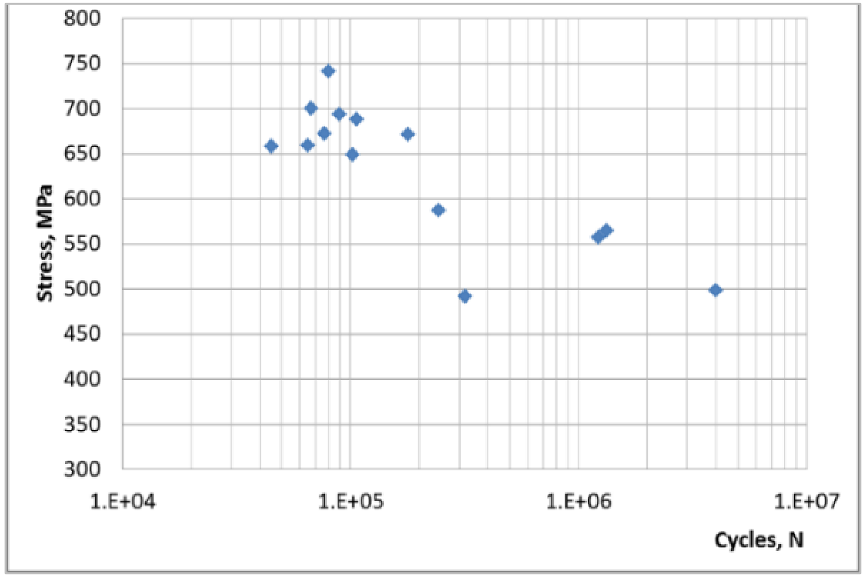
Zone	Impact strength J/cm^2, full size specimen 10x10mm
Weld	9-14
HAZ	16-19
Intact steel	24-26 (Steel COC - 25.4J)

Tension strength (UTS) for LBW joints about of average 1600MPa (St.Dev 63 MPa), and wire assisted LBW provided 1650MPa average UTS (St.Dev. 110 MPa). Tensile strength of original steel is about of 2GPa. Fractographic analysis indicated presence of welding microdefects, promoted lower strength data.

Impact resistance for weld metal dropped below 50% of initial steel value. Impact of HAZ better than weld core, but remains lower than original steel

Fatigue behavior of LBW samples





MIG process

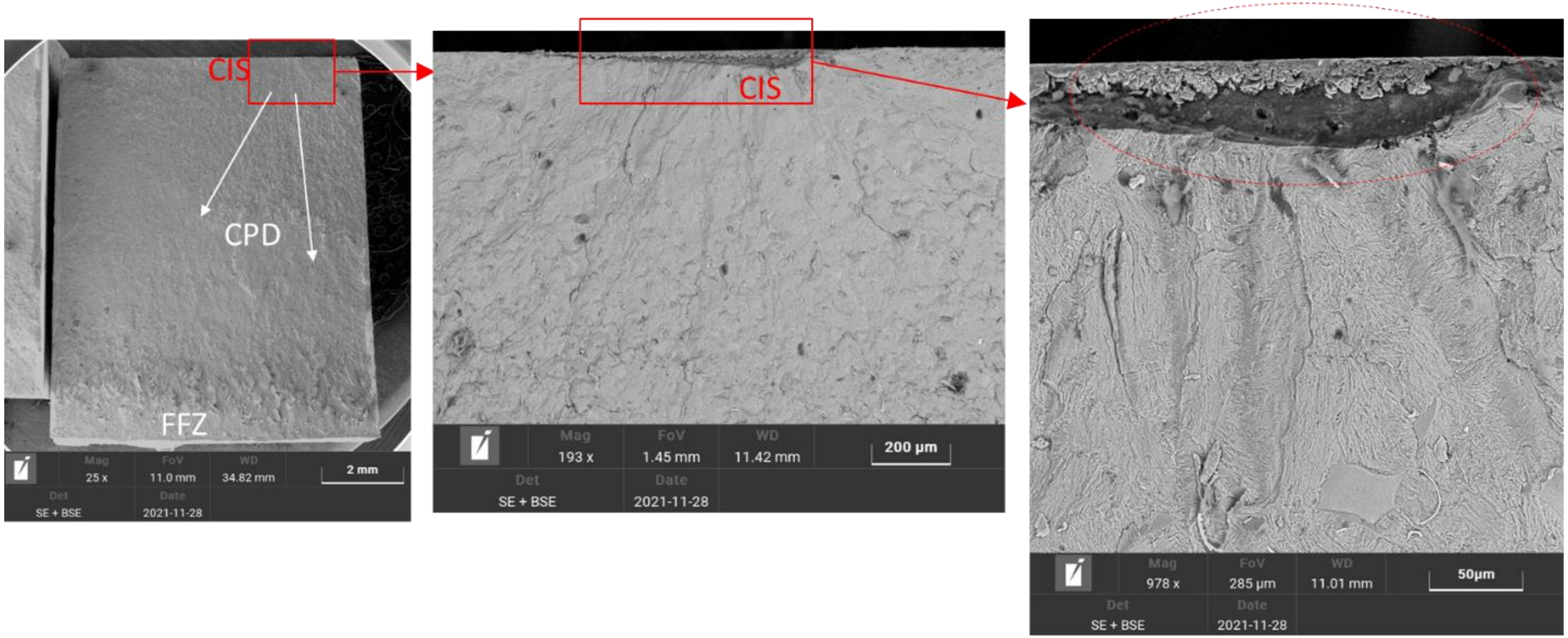
3PB test R>0, stress ratio (min/max) kept in range 0.02-0.08.

Arrowed markers designated run out specimens, tests stopped without specimen failure. Tests stopped when accumulated cycles reached 1-3M cycles.

Fatigue limit of the order of 1000-1100 MPa achieved on basis of more than 10^6 cycles.

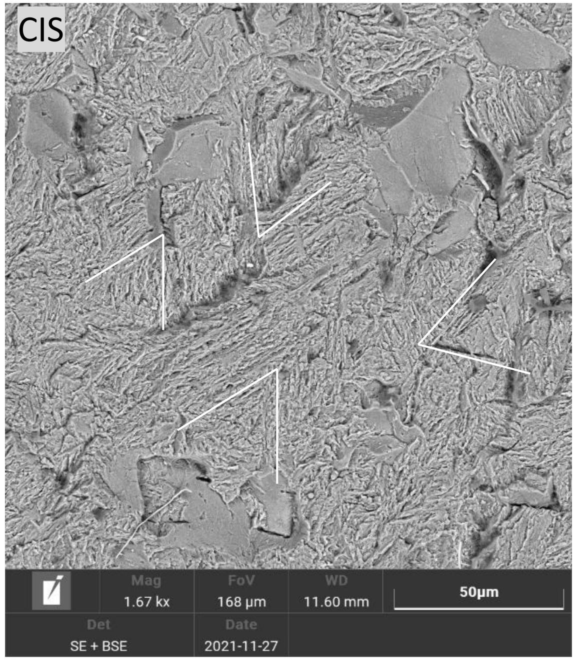
Fatigue performance of UHH armor steel, welded with conventional technique (MIG) was found significantly lower, than LBW technology.

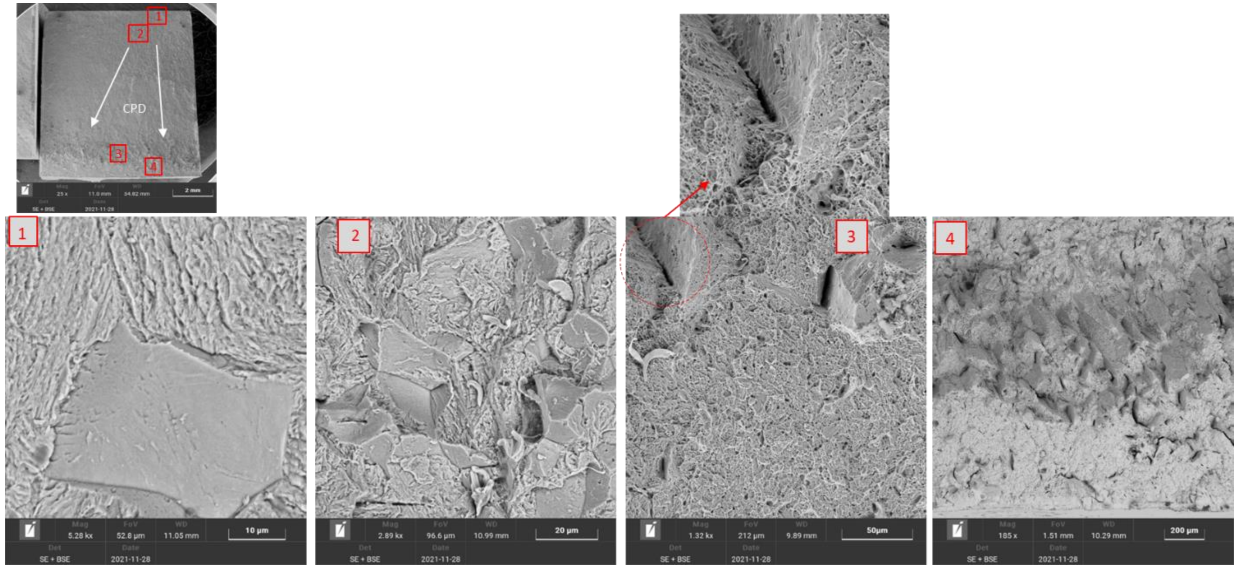
Post-Fatigue Fracture assessment – low data specimens

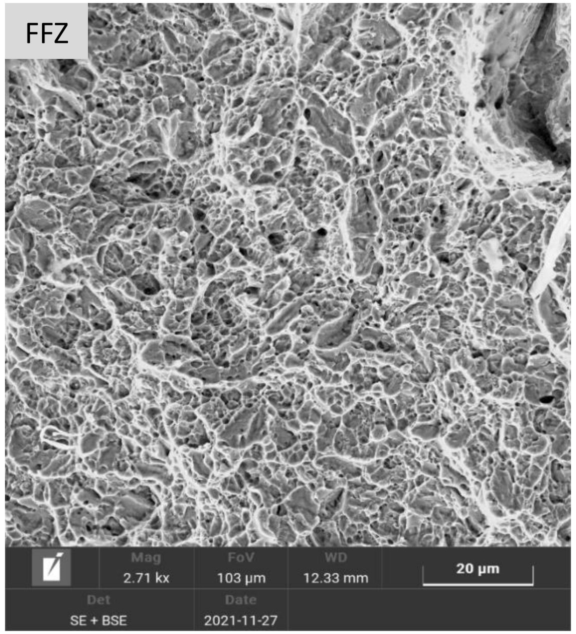


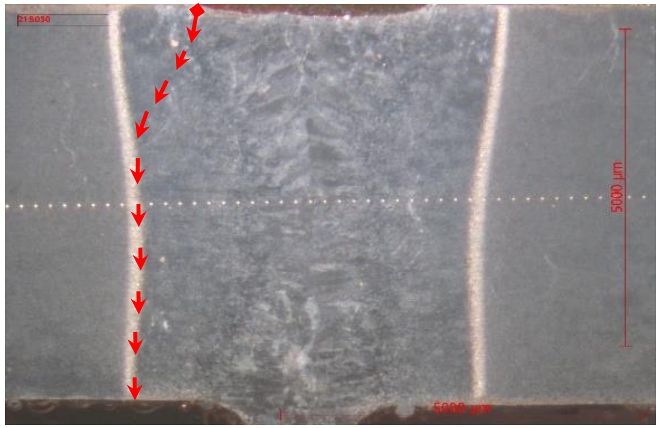
Specimen 5 was tested under 450 MPa (MAX stress) and failed after 0.25M cycles.
The reason for shorten run is surface defect, triggered premature formation of fatigue crack (right image).

Microstructural defects affected fatigue performance









Fracture crack starts from metallurgical defect (hot microcrack). At initial step crack grown through martensitic region (images 1 and 2) as brittle fracture. Then crack shifted toward less strong, tempered part of HAZ, images 3, where fracture is ductile mode. Discontinuities on gran boundaries associated with fast solidification and thermal stresses. Metallurgical micro-imperfections, induced by welding, were also involved in crack propagation path (im.4) on last step of fracture.

Summary

- Welding of UHH steels is subject of high interest, both for industrial and military customers.
- Current (primary) investigation is evident for applicability of LBW for high CE armor steels.
- Quality control appears to be critical for acceptable reliability of UHH armor joints.
- LBW accompanied with specific microhardness profile, when high hardness plateau of weld metal zone is quite different from MIG weld
- Fatigue data for LBW indicated strong potential of LBW on UHH steels.,
- LBW process may be implemented for joining of UHH steels, under tight quality control and development of particular process, adopted for specific products
- Mechanical behavior of weld zone is noticeable contributing factor for better ballistic performance of UHH weld joints.

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