

Laser Beam Welding of Alloyed Ultra-High Strength Steels

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Abstract: Stricter regulations for automotive car body engineering in point of CO₂ emissions and safety requirements demand the application of ultra-high strength materials for lightweight constructions. But components manufactured with new materials need established, cost-efficient and their benefits supporting production processes. One high potential process is laser beam welding with its high welding speed, enormous flexibility, low thermal distortion and slim weld shape. The combination of new materials on the one side, and challenging welding methods on the other side, makes a good understanding for the joining process as well as for the behavior of the base materials during the heat input necessary to create constructions which exploit the full lightweight potential and fulfill the extensive requirements. The following paper contributes to the safety applying of new materials into the car body manufacturing process by giving laser joining recommendations for a verified weldability.

Key words: Laser beam welding, chromium-manganese steels, ultra-high strength, press-hardening, lightweight, crash performance.

1. Motivation

The automotive engineering was characterized over the last decades by a continuous increase of the car body weight [1]. Different passenger advantages like entertainment systems, passenger comfort, but also electronic assistance systems to increase the active passenger safety are responsible for this movement. At the same time the worldwide regulations [2] demand a continuous reduction of the CO₂ emissions. These contrary-seemed construction targets for automotive engineers enforce new lightweight design possibilities. One way to reach this approach is the application of new high-strength materials which fulfill the requirements in a cost-efficient way with a high processability. Outokumpu Nirosta developed and established a new material group called Forta H-series with ultra-high strength properties for different forming operations like cold-forming or

press-hardening (“hot-formig”). For every grade the weldability is one of the key processes [3] to reach the targets in the automotive manufacturing process.

2. Cold-Forming Materials

For the production way of cold-forming parts Outokumpu Nirosta designed a new austenitic manganese-chromium alloyed steel group (MnCr steels). The material family comprises the Forta H500 and the worked-hardened Forta H800 and Forta H1000 whereby the numbers declares the yield strength. The mechanical-technological values represent a well aligned relation between a high strength and a very good elongation which are shown in Fig. 1 and Table 1. The MnCr steels have a face centred cubic (fcc) lattice structure depending on the concerted relation of the chosen alloying elements. The fully austenitic microstructure will be maintained after forming, deformation, and welding without forming martensite.

A specific balanced stacking fault energy results in the described stable austenitic microstructure. At the same time the conditions to avoid any kind of delayed

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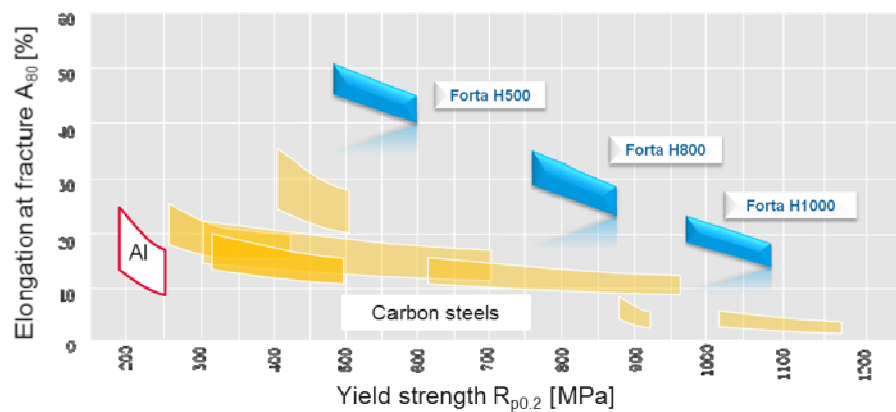


Fig. 1 Values of the austenitic cold-forming H-grades in relation to other construction materials.

Table 1 Mechanical-technological values of the austenitic cold-forming H-grades.

material	Yield strength $R_{p0.2}$ [MPa]	Tensile strength R_m [MPa]	Elongation A_{80} [%]
	typical	typical	typical
Forta H500	530	900	51
Forta H800	800	1000	31
Forta H1000	1000	1200	13

cracking are fulfilled [4]. Instead of the well-known hardening effect of metastable austenitic stainless steels (or called CrNi steels), where the austenite converts into martensite (TRIP = transformation induced plasticity), the new MnCr steels use the TWIP hardening effect (twinning-induced plasticity). The hardening works by building up more and more twins in the microstructure keeping at all time an austenitic microstructure. As a result it is possible to reach over 2,000 MPa in the hardened material during a forming operation or a crash situation.

The alloying element manganese works as an austenite former and creates further benefits like an increase of strength as well as ductility. Furthermore manganese has the effect of preventing the material from the generation of phases sensitive to hot-cracking [5]. The second main alloying element is chromium which influences the mechanical-technological values in a positive way [6], support the solubility and homogeneity of the other elements and build up a chromium-oxid passivation layer on the steel surface

which is well-known from stainless steels. The material is delivered bright and does not need a further (zinc) coating because of this natural and repassivating corrosion protection layer. This fact avoids welding irregularities. With applying a typical cathodic dip coating on the manufactured components, the passivation layer presents a very good corrosion protection system even after a lattice cut or a stone chipping. The passivation layer avoids an undercut of the injured dip coating because of its repassivating properties.

The MnCr steels feature a very high energy absorption combined with a high impact resistance. As one example Fig. 2 illustrates a dynamic high-speed axial crash of a square profile manufactured with a Forta H800 in a thickness of 1.5 mm. As a result the profile shows a great forming behavior and a high energy absorption combined with crack-free welding and forming zones.

During the impact situation, the full austenitic microstructure and the TWIP hardening effect of the

Dynamic axial-crash of Forta H800 (1.5mm) as a square-profile

Test parameters: Drop height $h = 4.0\text{m}$, drop weight $m = 433\text{kg}$, Speed $v_0 = 30.73\text{km/h}$



Fig. 2 High-speed axial crash of Forta H800.

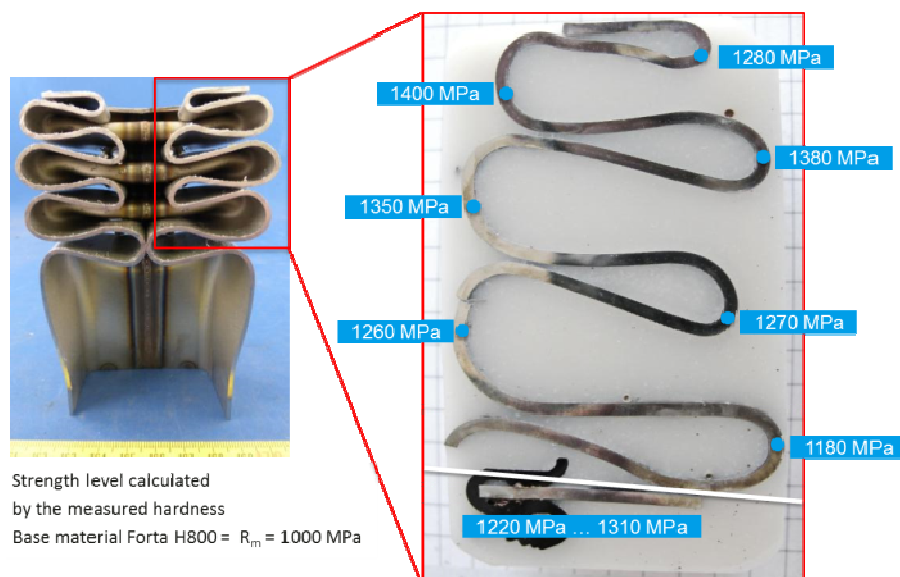


Fig. 3 Resulting hardness after the axial-crash of Forta H800.

Forta H-series develop their full benefit: The material will harden in relation to the impact force and subtend a high resistance to the impact simultaneously absorbing the impact energy. Fig. 3 illustrates the hardening of the axial crash from Fig. 2.

Therefore a high direct lightweight potential results. For the example of a b-pillar it can be shown in relation to a press-hardened steel (22MnB5 with $R_m \approx 1,500\text{ MPa}$) that a thickness reduction of 35% is possible under retention of the intrusion level but with a more

ductile and crack-free crash behavior.

The MnCr steels enable further lightweight for transport applications because of their possibility to form complex parts with an ultra-high strength steel group. It is possible to reach a lightweight potential of up to 50% for complex cold forming parts like longitudinal beams, wheel houses, seat structures, channels, tanks or battery packs. Moreover the Forta H-series enable further constructive lightweight by exploiting so far not used geometrical degrees of

freedom. Other design ways and manufacturing processes like roll forming or hydro-forming in combination with a laser beam welding process decrease the weight and increase the resulting component stiffness as well as the passenger safety in general.

3. Laser Beam Weldability of the Cold-Formable MnCr Steels

In general, austenitic MnCr steels are suitable for welding in similar as well as in dissimilar welds. Especially laser beam processes with their high welding speed and locally concentrated heat input offer

a great potential in combination with those austenitic steels and their physical properties.

First investigations of laser beam welded MnCr steels are described in Ref. [7]. Laser beam joints with MnCr steels as a base material offer a high transmission of power under every direction of loading and a ductile fracture behavior during destructive testing, as shown in Fig. 4.

Laser beam welded sheets exhibit the typical behavior of welded austenitic materials under metallography inspection with a hardness measurement. A softening in the weld seam can be detected, as shown in Fig. 5. The often visible behavior



Fig. 4 Ductile behavior of a laser beam welded cross-tensile-sample.

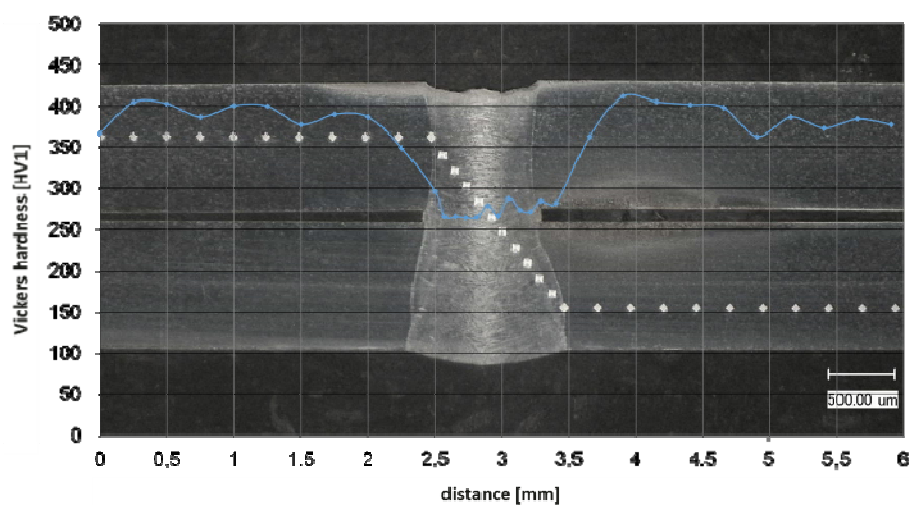


Fig. 5 Hardness curve and micrograph of similar laser-beam welded H800 in lap joint condition.

of ferritic carbon steels with an increase of hardness in the heat-affected and welded zones, often combined with brittle effects, cannot be detected for the austenitic materials.

Metallurgical background of the visible softening effect is that the welding works like an annealing process and reverses locally the twins in the microstructure. As a result the hardness of the Forta H500 base material is reached in the welded zones. With the benefit of a full austenitic microstructure in combination with a TWIP hardening effect, the welded zones are not a weak point in a construction, in fact they are a further crash and safety potential. The explanation can be represented with a high-speed three-point bending test where a cup profile was used. The profile was worked out as a tailored welded blank

of a Forta H800 with an H1000, and then spot-welded to a zinc-coated micro-alloyed steel as a locking plate. Fig. 6 shows a hardness measurement with the comparison of a non-tested and an impact stressed profile.

A hardening can be detected after the impact. The twins restart building in the microstructure and the hardening speed is much higher for the areas with a lower number of twins, here the laser welded seam. Therefore the joint areas are not the weak point in a construction. During a critical impact the joints reach the hardness of the base material again. Therefore the cold-formable austenitic Forta H-series fulfill in welded as well as in base material conditions highest safety requirements for intrusion and crash relevant components of a car body.

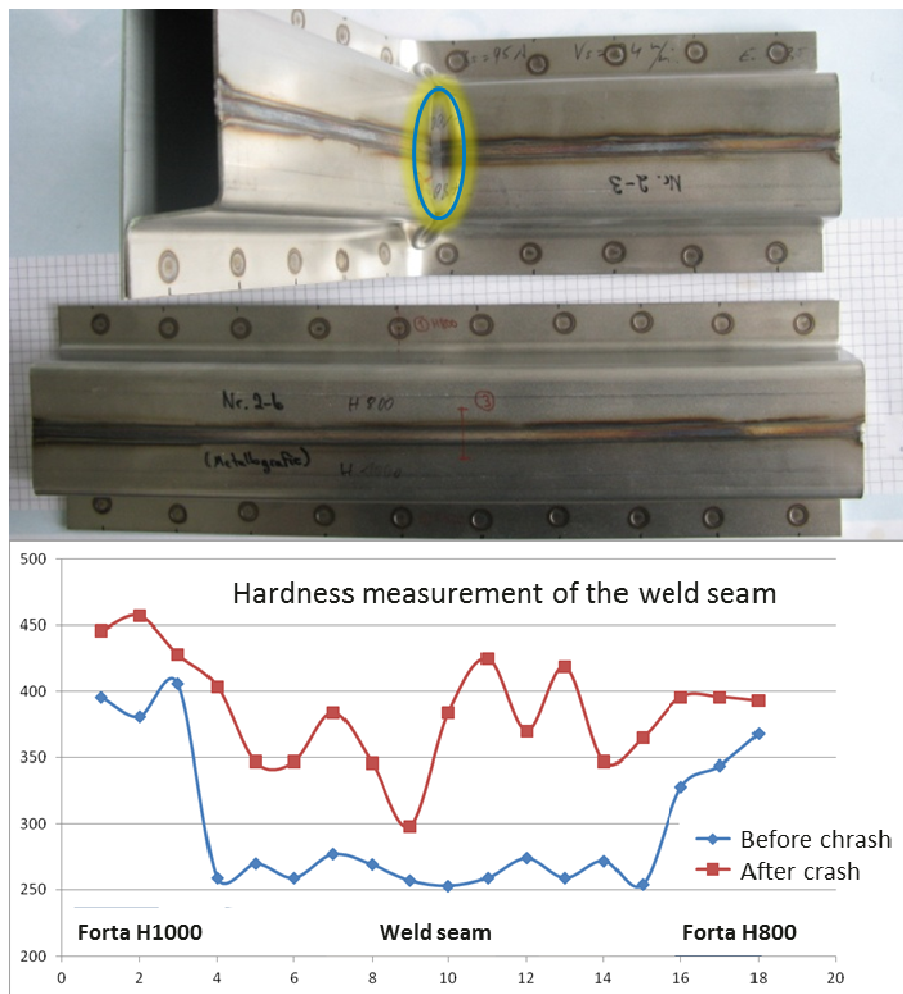


Fig. 6 Comparison of hardness for a welded and then impact-loaded sample.

The Forta H-series reached successfully the general material evaluation process according to SEP1245 [8] as well as the confirmation of the laser-beam weldability according to SEP1220-3 [9]. The RWTH Aachen University, ISF Welding and Joining Institute supports the complete process of the testing and documentation guideline for the laser beam weldability. Different guidelines and test results for similar and dissimilar joining combinations are available to support the processing industry. Further information about metallurgical aspects and welding recommendations are given in Refs. [10, 11].

4. Hot-Forming Materials

The Forta H1200PH represents a complete other manufacturing way and material design. The material reached after hot-forming, or often called “press-hardening”, a yield strength level of $R_{p0.2} \approx 1,200$ MPa and “PH” specified the ability for press-hardening. This stainless steel has a ferritic-martensitic microstructure in initial state and changed after the hot-forming process into a martensitic-based matrix with austenite parts. The material is based on a steel containing 0.45 wt.% carbon and 13 wt.% chromium 1.4034 (X46Cr13). The material advantage is the combination of a very high tensile strength ($R_m \approx 1,850$ MPa) combined with an extra-ordinary elongation ($A_{80} \approx 13\%$) after hot-forming, as shown in Fig. 7.

Other hot-forming process parameters in comparison to established materials like the manganese-boron steel 22MnB5 are necessary: hot forming starts with austenitization at 1150 °C, subsequent quenching in the mould, and tempering at 400 °C for five minutes. Nevertheless this adjustment of hot-forming parameters results in different new advantages: The chromium alloyed material does not need a further scale-resistance coating like aluminum-silicium (+AS) and can be therefore used for fast heating processes with induction or conduction. No additional diffusion time is necessary. Moreover the stainless steel functions as an air hardener what results in very homogeneous and repeatable material properties. Furthermore the low martensitic starting temperature (M_s) supports the hot-forming of very complex parts because more process time for the forming operation is available. The martensitic stainless steels are industrial available also as thin sheets (down to 0.5 mm) over a large width (1,250 mm) what permit further lightweight potential. But also thick plates up to 6.0 mm are possible for hot-formed pressure tanks.

The building of austenite islands in the martensitic based microstructure after hot-forming is a key advantage of the Forta H1200PH, as shown in Fig. 8.

This effect is responsible for the high elongation and excellent properties during subsequent three-point bending tests where high bending angles over 90° can

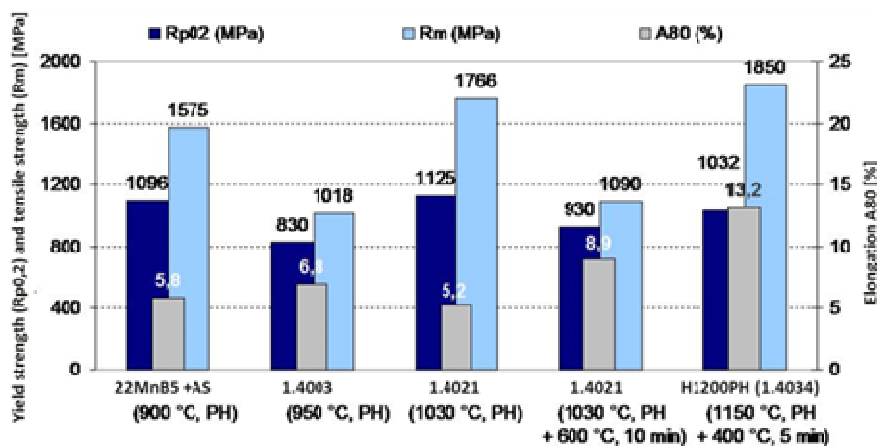


Fig. 7 Mechanical-technological values of different hot-formed steels [17].

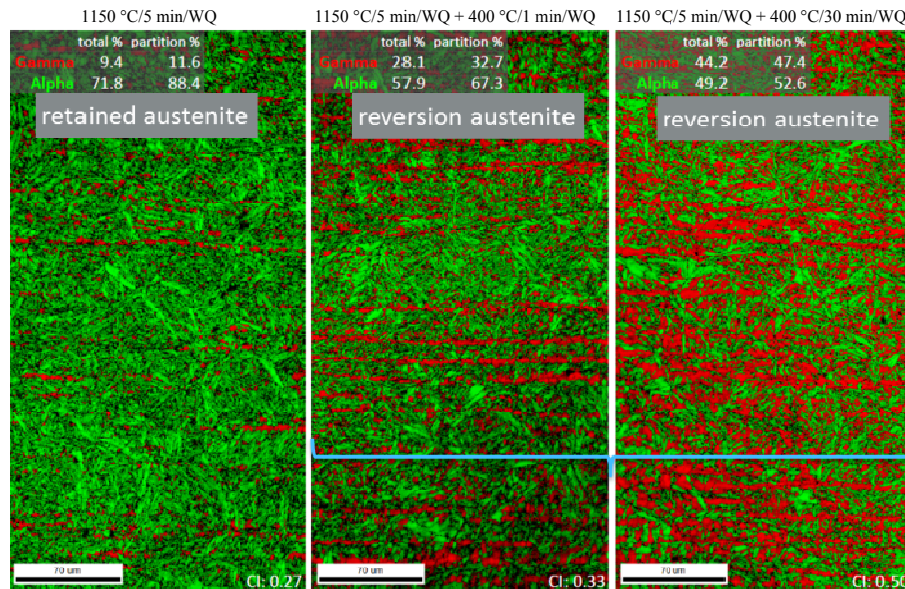


Fig. 8 Retained and reversion austenite after hot-forming and annealing of FortaH1200PH.

be reached. Further a good crash performance is given by the described microstructure effects.

Former literature described general weldability of martensitic stainless steels with up to 0.46 wt.% carbon as limited [12-14]. Therefore the material requires some special assistance in point of weldability although the material was proven to be suitable for laser beam welding which is the only fusion welding process possible to be applied to this class of steels. A weld heat treatment was proven to be beneficial to the mechanical properties of the welds.

5. Laser Beam Weldability of the Hot-Formable Materials

Two different ways of manufacturing seem to be suitable to apply the Forta H1200PH as a hot-formed component for transport applications and car body engineering: The first one uses laser beam welding as a butt joint in initial, cold-rolled material state to create a tailored welded blank which can be hot-formed afterwards. For the second possibility the base material is hot-formed in a first step to create the component and then welded as a lap or a butt joint to other components of the car body. Therefore it is important to ensure the weldability of the base material in initial as well as in hot-formed state.

Short thermal cycles should be preferred for welding martensitic stainless steels in general. But to avoid cold cracks and high hardness gradients, a material-suitable heat-control is desirable. To relax the tetragonal martensitic microstructure, a pre-heating to martensitic starting temperature (M_s) combined with an intercooling to 150 °C-200 °C after welding and a following tempering below the temperature of the dissolution of the alloy carbides is appropriate [15, 16]. Further references to the welding behavior of those materials and the calculation of the martensitic starting temperature can be given with Refs. [17-19].

The following investigations were worked out in the AiF-funded research project FOSTA P905 “Investigations on fusion welding of high-strength chromium steels with a martensitic microstructure by using laser beam and gas-metal-arc-welding processes” (IGF project number 17.433N). To test different ways of heat input and seam geometry, carbon dioxide laser as well as disc laser were used as beam sources. The welding parameters are presented in Table 2.

The results of hardness measurement across the weld seam and the heat affected zones for different thermal treatments of the H1200PH are displayed in Fig. 9. The hardness of initial cold-rolled sheets which are laser welded is shown with black graphs (rhombs) and

Table 2 Applied welding parameters for laser beam welding of H1200PH.

Parameter for $t = 1.5\text{mm}$	CO ₂ laser	Disc laser
Beam power P_L [kW]	2.5	4
Spot diameter d_F [μm]	340	610
Fibre diameter D_F [μm]	-	300
Beam diameter D_S [mm]	17	-
Focal length f [mm]	200	400
Welding speed v_s [m/min]	5	4
Input energy E_s [kJ/min]	30	70
Joint type	Square butt joint Lap joint	Lap joint
Seam width b_s [mm]	0.65	1.1

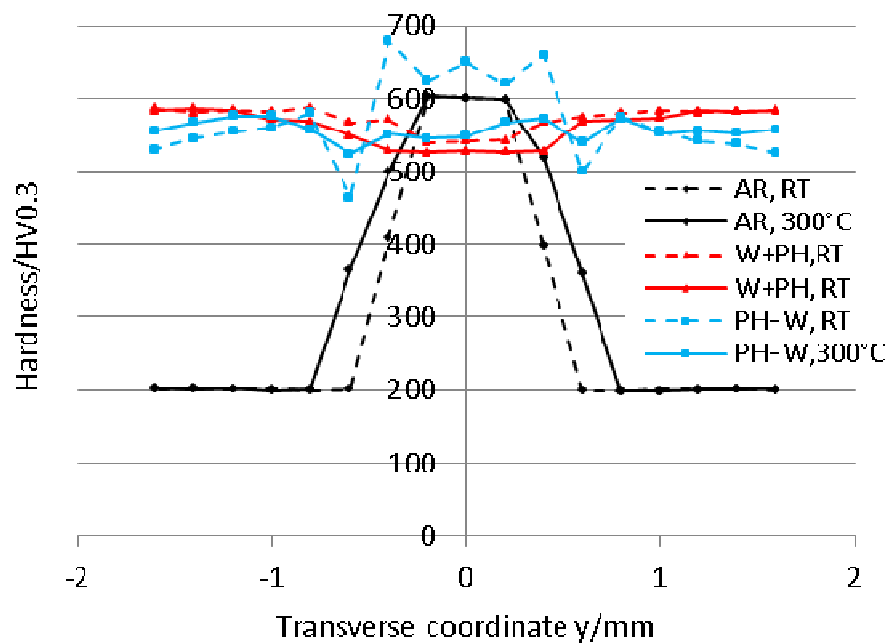


Fig. 9 Hardness curves of Forta H1200PH for different thermal treatment conditions.

clarifies an increase to 600 HV0.3. This hardness gradient is well-known in the mentioned before literature and results in a cold crack behavior. But the blue graphs (squares) illustrate the hardness of welds in

press-hardened condition. Without pre-heating a dip in the heat-affected zone by 80 to 110 points is observed. The dashed lines represent to welds produced without pre-heating, solid lines to pre-heated welds (TMs =

300 °C). Especially for the laser-welds in press-hardened condition, the pre-heating shows a positive influence and grades the hardness in the weld zones to the level of the base material hardness in hot-formed condition.

The fatigue behavior is an important investigation to test the lifetime conditions of welded structures and was analyzed with a cyclic test under constant amplitudes. The test were carried out using a resonance pulsator, which enables a test frequency of about 100

Hz depending on the specimen's stiffness, and a load ratio $RF = 0$. A crack length of about 0.5 mm was chosen as failure criterion and could be detected by a test frequency drop off by 1 Hz. In the case off having samples without rupture, the test was stopped at $N = 1 \cdot 10^7$ cycles. The specimen geometry according to SEP1240 [20] has been chosen but modified by a butt joint vertical to the cyclic loading direction, Fig. 10 right side. Fig. 10 also represents the influence of the heat-control.

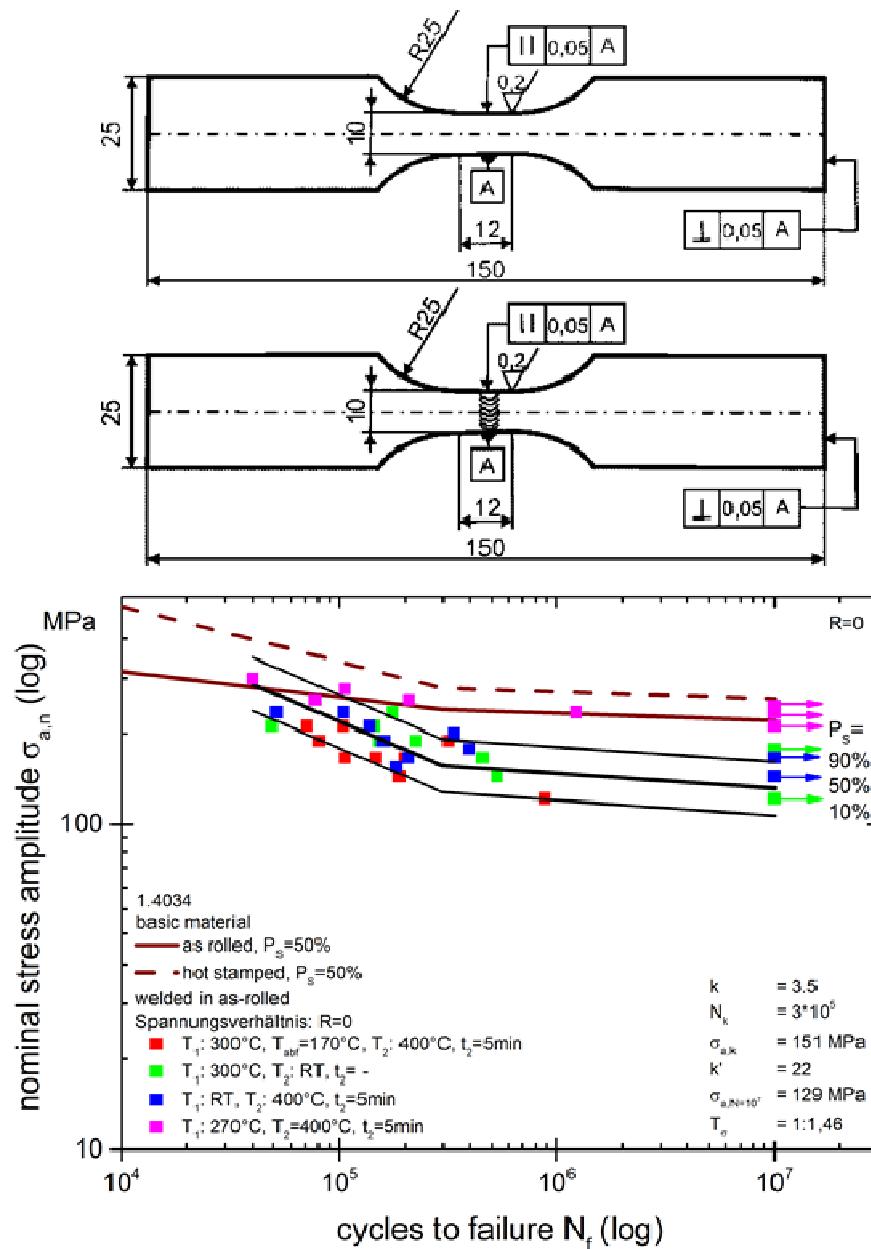


Fig. 10 Chosen sample geometry (above) and resulting fatigue behavior (below).

As a result of this project extensive guidelines about how to weld and how to treat the ultra-high strength grade were created. The presentations at the project-closing colloquium [21-23] enlarge significant the knowledge of the former literature and add new manufacturing possibilities for the processing industry.

6. Conclusions

Outokumpu's new Forta H-series combine ultra-high strength alloyed materials with different microstructures and hardening effects for different manufacturing processes like cold- or hot-forming. The weldability depends on the microstructure and alloying elements of the respective chosen material. But independent, the process of laser beam welding with its specific advantages occupies a key role by ensuring the weldability of the materials or different material conditions. Therefore laser welding enables the production of lightweight and crash-safety components with new ultra-high strength materials for future car bodies and transport applications.

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