High Quality Welding of Weight Optimized Passenger Car Bodies – an Important Enabler for Producing the Most Fuel Efficient and Environmental Friendly Products in the Business

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1 Improving the Environment through Lightweight Body Engineering

Improved car body properties for energy absorption at crash and increased torsion and bending stiffness are factors that invariably result in added body mass. Normally the car body has to be up-graded by thicker sheet components and add-on reinforcements. Through the years this has lead to a continuous weight growth of the vehicles, something that is contradictory to those environmental aspects that are being discussed in today's society. To counteract an increase in toxic emissions and fuel consumption, the European Community has decided upon a directive which says that the average CO_2-emissions from a company's overall fleet of produced cars must not exceed 140 g per driven kilometre in 2012, a requirement which will be further accentuated to 95 g CO_2/km by the year 2020 [1].

Besides obvious measures like improved engine technology (e.g. hybrid power and electrification) and alternative fuels (LNG, ethanol E85, bi-fuel etc.), a thorough weight reduction of the car body will be necessary. To achieve this there are three main solutions:

- To reduce the overall number of body parts
- To dimension for thinner sheet gauges
- To substitute steel sheets with low density materials

All the steps mentioned above are possible to carry out by utilizing smart design solutions, including innovative joining methods. This is already done to some extent today, but if we take a look at the palette of available joining methods [**Fig. 1**], it is easy to understand that it will cause substantial problems for the design engineer to select the appropriate method in each and every case.

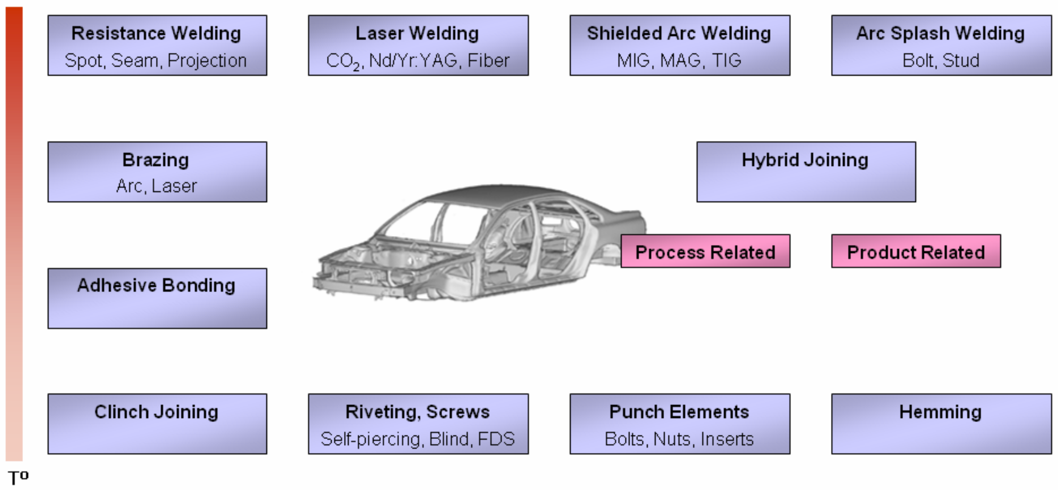


Figure 1. Joining methods currently used in the body assembly process.

2 Establishing the Volvo Joining Network

With the background described above, and realizing that new materials and materials combinations were necessary for requirement and performance fulfillment in up-coming products, the Volvo Car Corporation (VCC) management ordered that a strong focus should be put upon the development of "new" joining methods and matching equipment. In addition to this, joining activities should also be performed which improved the quality in already existing products and processes.

For this reason the VCC Joining Network was established in May 1998 [2]. A number of specialists, both white and blue collars, representing various techniques and competencies, were grouped together. They don't only represent the body engineering portion of the company, but the idea is that this Network shall cover all methods used for the assembly of cars, regardless where in the production flow these operations take place.

One of the most crucial things concerning the implementation of new joining methods in production, is to be able to make complete process verification in advance. Therefore the Joining Network, located as a part of the VCC Pilot Plant, is fully equipped with various machinery [**Fig. 2**]. The equipment could be divided into two categories:

- Equipment for process development, which means robotized guns and stationary machines for the optimization of process parameters (e.g. welding lobes, stroke, setting forces etc.) and the manufacture of overlap- and H-specimens for static and fatigue testing. The equipment covers the following techniques: resistance-, arc- and laser welding, mechanical joining like clinching and riveting, adhesives, fasteners and screw joints.
- Equipment for process validation, meaning fully equipped production cells with automated assembly equipment. They are in the type of “framing stations” with flexible equipment, which means that it is possible to roll in and roll out the intended installations which could be in the form of robotized welding and clinching guns, robotic carried adhesive bonding or laser nozzles, etc. In these cells it is also possible to test and evaluate different systems for seam tracking and on-line monitoring.

Figure 2. Equipment for process validation for high volume production, available at the VCC Pilot Plant facilities.

Close to the assembly installation there is a small test facility equipped with instruments for cross-sectioning, microscopy, tensile testing and weld hardness measurement, in order to rapidly check the quality of the joint made.

An urgent work item put upon the Joining Network was to create procedures for joinability. Traditionally it is more or less state-of-the-art, that new material grades are tested concerning formability. Corresponding activities on joinability have up until some years ago not have the same magnitude of focus. However, it is important that not only the suitable process parameters are recorded, but also design information like static and fatigue strength of the joints, as well as their performance at high strain rates. Such activities are nowadays State-of-the-Art procedures within VCC, and correlated with standardization issues and existing databases [3].

3 Process and Product Validation of Welded High Strength Steel Sheet Combinations

The new ultra high strength steels (UHSS) are presenting the welding engineer with new challenges, i.e. smaller welding windows (less robustness), more complicated fracture mechanisms, potentially weaker welds, different fatigue behaviour and more complex quality checking in production. The classic problems at resistance spot welding, such as electrode alignment, the presence of adhesives and sealants as well as various types of zinc coatings have a larger effect on the welding of UHSS compared to conventional mild steels [4]. From a long experience of spot welding of high strength steels the following has been concluded in order to obtain a successful result:

- Increased electrode force
- Increased welding time
- Decreased weld current
- Optimized hold time to avoid brittleness
- Pulsed welding is favourable
- Larger electrode caps are recommended

One of the major challenges in the resistance spot welding of the latest Volvo models was the increased use of hot-stamped, Boron alloyed steels. This material is not a heavily alloyed multi-phase material, but it is the surface conditions that create the major problems for the spot welding process. The hot forming process leads to the formation of a thin oxide layer on the surface, usually referred to as oxide scales. This must then be removed, which today usually is done by a shot-blasting operation. Other possibilities previously used were to etch or pickle the surface. However, these are expensive and environmentally un-friendly processes and therefore less suitable.

One of the characteristics of a shot-blasted surface is the variation of the electric resistance of the surface (**Fig. 3**). This can vary both between components as well as within the same component. The variation of the electric resistivity of shot-blasted surfaces is sufficient to disturb the spot welding process and significantly decrease the weld quality of the spot welds. Previously, pickling the oxide scale off the surface solved this problem, but this is not an option anymore. Today there are two main solutions, one is to use AlSi-coated material, which prevents scaling and the other is to use an adaptive weld timer. Both of these actions are today standard in VCC's products and production equipment. The use of AlSi coated material is the simplest solution as then conventional weld timers can be adopted.

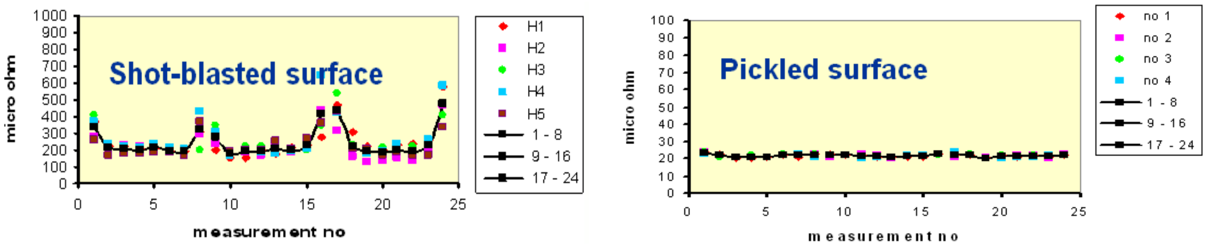


Figure 3. Significant difference in surface resistance between a shot blasted (left) and pickled (right) body component manufactured through hot-stamping.

However, AlSi coated material is very difficult to weld using conventional robotized gas metal arc welding (GMAW), but feasible if the Cold Metal Transfer (CMT) technology is being used. This was proven when there was a need to arc weld a portion of the A-pillars of the new S60 and V60-models [5]. When using a conventional gas metal arc procedure it showed to be impossible to get stable arc conditions, especially if the AlSi-coated part was positioned as the base sheet. The cathode spot seemed to be moving around, and therefore CMT was investigated as an alternative. Cold Metal Transfer is a type of pulsed welding where the filler wire simultaneously is moved back and forth at high speed (50 Hz). Due to that the arc is momentarily extinguished, the current is kept low and the heat input is reduced, it represents a suitable method for welding in very thin sheet gauges. The rearward movement of the wire also assists droplet detachment, and the weld spatter is considerably reduced, which in turn means less re-work in the body shop [6]. In a comparative test with a 1.45 mm thick zinc-coated DP600 material positioned upon a 1.75 mm thick AlSi-coated Boron steel, the CMT method proved to be much more robust compared to the traditional arc welding technique (**Fig. 4**). Also the welding speed could be increased.

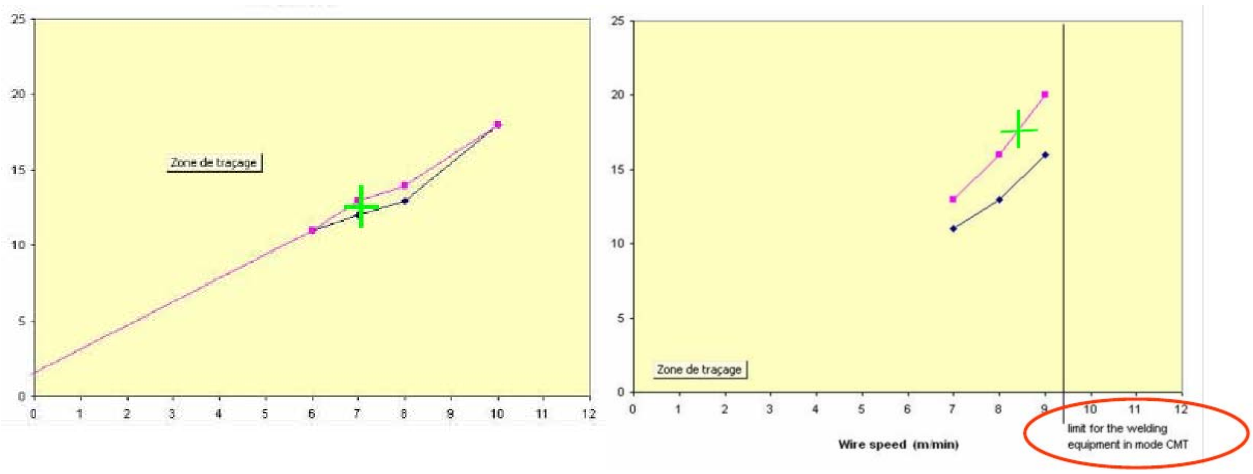


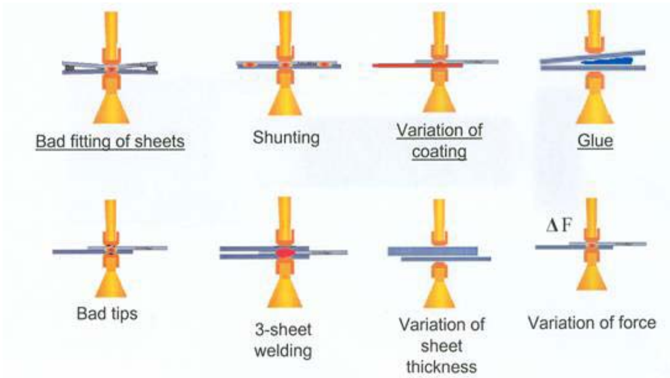
Figure 4. Welding speed as a function of wire feed rate showing the robustness of arc welding of AlSi-coated Boron steel; conventional GMAW (left) and CMT (right).

4 High Performance Spot Welding Equipment for High Volume Car Body Assembly

As described above the new Volvo model programme contains an increased amount of UHSS materials in the car body structures, with a high number of hot-stamped Boron steel components and an increased usage of epoxy based structural adhesives and laser welding [7]. Therefore the complexity of spot welding and monitoring of the process has increased and made it necessary to re-build the body assembly line in the Torslanda plant, introducing some of the newest technology and equipment available. When starting the EuCD program with its forerunner, the new Volvo S80 luxury sedan, it was decided to use adaptive weld timers to take care of possible disturbances (**Fig. 5**). With such a system it is not only possible to get more benefits than just reacting on disturbances, but also to monitor the welding process and its condition at the same time.

Figure 5.

Examples of possible causes for poor weld quality, which can be counteracted by a spot welding gun which utilizes an adaptive weld timer.



Adaptive weld timers work in the way that the system measures the resistance, in the equipment itself and the sheet components that are to be welded, and compares the voltage curve to a calibrated one. The system then reacts either by increasing the current or prolonging the welding time if there are any deviations from the nominal values (**Fig. 6**).

Calibration is normally carried out on coupon level which makes it possible to generate calibration curves in advance, before going into real prototype build. Sometimes complete car bodies are used in order to get a more accurate calibration. The drawback is that it will be more difficult to detect if the weld nuggets are good enough, provided you are not allow to tear down a lot of car bodies just for the calibration purpose. The downside to perform calibration on coupons is that you need to have a big stock off different coupons (thickness and material grade) and there are a lot of logistics in handling the coupons, which could result in the delivery of the wrong coating/material/thickness or just mixing up the different test coupons.

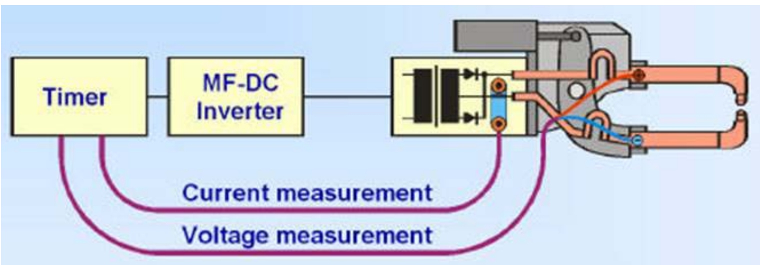


Figure 6.

Principle sketch of a weld timer arrangement with current and voltage measurement.

At the same time as the decision was made to go for new weld timers, the plant also invested in a large number of electric servo guns and several tests were made in order to prepare for the new F-packs (Functional packages = robot + timer). The main reason for choosing the electric driven gun was the increased speed and the accurate movement offered (**Fig. 7**), which in turn reduced the number of F-packs needed. This implies a substantial cost saving for the new assembly line. For a framing station, time savings can be up to 30% and for a re-spot ditto it is 10-12%, which represents the total time (welding + movement). For the welding cycle itself one can save 300ms/spot just from a reduced squeeze time.

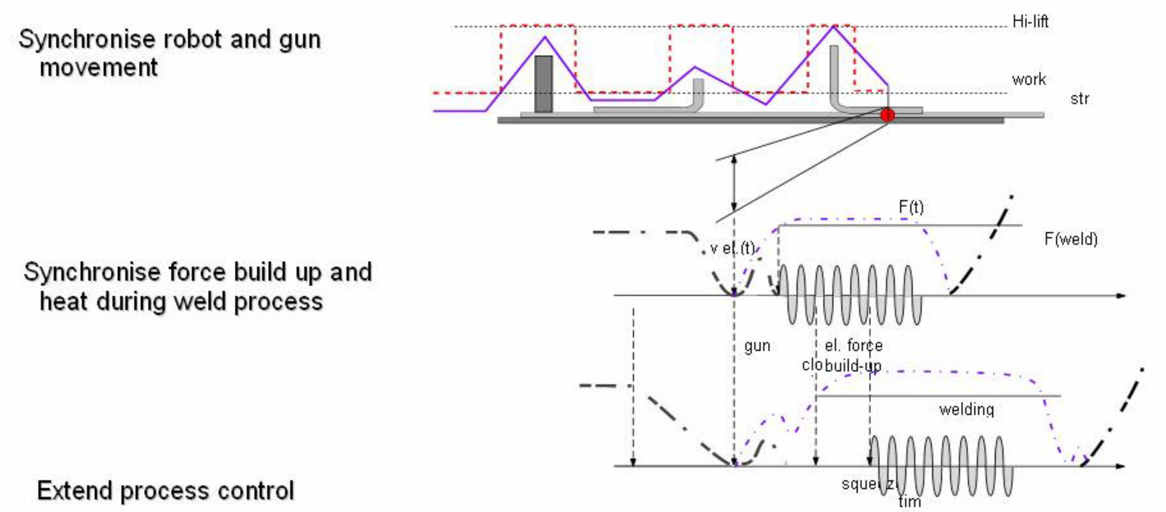


Figure 7. The principal operation of an electric servo gun.

In the first tear-down test, during the pre-series build, it was possible to establish that 95% of the spot welds were OK. Here it should also be pointed out that some of the NOK spots were to be related to bad robot positioning, such as edge welds or “weld-in-weld”, something which can not be influenced by the adaptive timer system.

Today the output from the body shop is in the range of 98-99% OK spot welds, and the next step in quality improvement will be to run a weld spatter optimization program. For that reason the calibration curve will be done on the first spot in the weld sequence and not as today on the second one. The main driver for this approach is to get the weld nugget closer to the minimum acceptable diameter, avoid spatter contamination and not the least save a substantial amount of electric energy.

The numbers of new pieces of equipment installed in the EuCD line at Torslanda for the flexible production of the models V60, V70, XC70 and S80 are summarized in **table 1**.

Table 1. Production equipment in the EuCD assembly line.

Robot equipment	Numbers
Pneumatic welding guns	161
Electric servo welding guns	105
Bosch MFDC* inverters	152
Bosch adaptive inverters	27
Matuschek adaptive inverters	80

*) MFDC = Medium Frequency Direct Current

5 New Aspects on the Quality Assurance of Spot Welds

For quality assurance of spot welds in high volume series production both destructive and non-destructive methods are being used. Regarding the later, chisel testing is a method generally used among automotive manufacturers, where a chisel is pushed in between the sheets close to a spot weld. With this method poor welds and zinc soldering can be detected, and afterwards the parts are adjusted back to their normal position. However, due to the high strength of hot-stamped parts it has shown to be almost impossible to insert a chisel in the above described manner. Therefore other non-destructive test (NDT) methods had to be considered, which in practice means that nowadays ultra-sonic (US) checking is the normal procedure to evaluate the spot weld quality in metal stack-ups involving one or more hot-stamped parts. However, the introduction of Boron alloyed steels make the use of ultra-sound measurements more complex compared to when the method is applied to mild steels. The occurrence of centre pores is for example more frequent [**Fig. 8**]. Such pores are not classified as defects, but can easily be interpreted as other defects in the ultra-sonic checking. To distinguish between a good weld with a centre pore and a defect one requires skilled, well-trained operators.

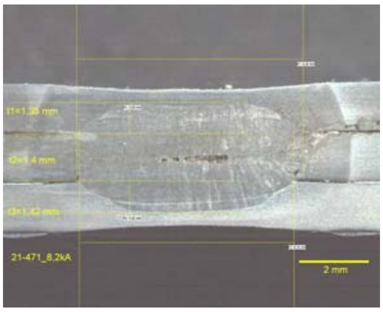


Figure 8.

Small centre pore in a Boron alloyed steel sheet combination.

Also for other difficult-to-reach spot welds, ultra-sonic checking is the preferred technique, which has resulted in that 25% of the 4,170 spot welds in a V70 body structure are quality assured in this manner.

For the destructive checking, which is done less frequent, other issues occurred. These were already identified in 1998 when the first generation S80 model was launched [8]. That body presented a rear bumper beam solution comprising of two 1.2 mm thick shot-blasted Boron steel parts spot welded together. If one was to follow the traditional acceptance criteria, stating that a full weld plug should be torn out from one of the sheets, several spot welds connecting Boron steel parts to other high strength steel (HSS) components would be classified as "not approved". Therefore partial plug failures (PPF) and interfacial fracture (IF) had to be accepted provided that a rough fracture zone could be detected. This however showed up to be an uncertain evaluation criteria, as the fracture surfaces were difficult to read even if a magnification device was used. Therefore a new requirement, the so-called "weld penetration depth" was establish. To validate this type of demand, a section cut analysis of crucial welds is necessary [**Fig. 9**]. A minimum weld penetration of 40% of the sheet thickness is required for 2-sheet metal stack-ups and corresponding 30% of the thickness for the outer panels in a 3-sheet stack-up.

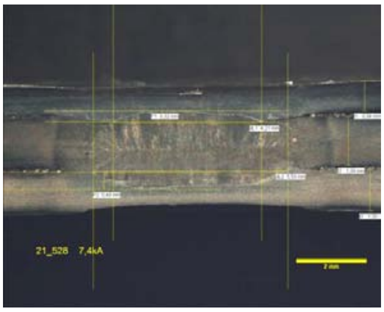


Figure 9.

Cross section analysis of a 3-sheet metal stack-up indicating sheet thickness, nugget diameters and weld penetration depth.

6 Utilization of Laser Welding in Boron Steel Intensive Structures

Despite all the actions described above some spot welds positioned in critical areas were susceptible to failure at high loads at crash testing during the development of the new Crossover Utility Vehicle (CUV) - XC60. Due to the severe loading conditions at a potential side impact, the stress concentration around some of the spot welds are prone to result in brittle fractures in the welds and in the sheet material close to the weld circumference. To counteract these fractures and decrease stress concentration, the spot welds in the mid-area of the hot-stamped, Boron steel B-pillar were substituted by 590 mm (front flange) and 500 (rear flange) continuous laser welds [9]. These joints are actually three sheet metal stack-ups as the body skin panel is welded in the same operation. This means that the laser weld is a fillet weld between the body side and the B-pillar reinforcement, but an overlap weld between the B-pillar reinforcement and the B-pillar inner (**Fig. 10**).

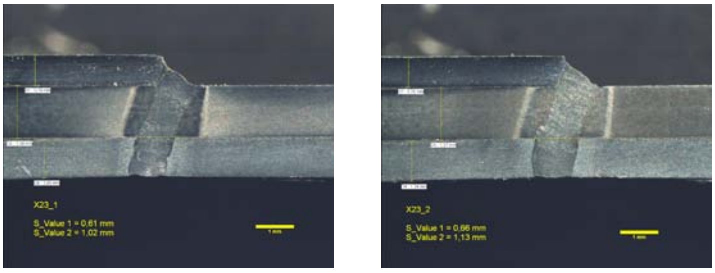


Figure 10.

Superior quality of the laser welds connecting three separate parts in the B-pillar structure.

But the XC60 body structure also presents some other innovative solutions combining high strength Boron steel components assembled through laser welding [10]. One such solution is the design of the windscreen- or A-pillar which presents a challenging engineering task as it implies some contradictory requirements. On the one hand, the A-pillar should be strong and stiff to act as a part of the safety cage at rollover accidents, on the other it should be as slim as possible to enhance the driver's visibility which is a crucial aspect from an active safety standpoint. To solve such a challenging task, hot-stamped, press-hardened Boron steel alloyed parts with ultimate strength around 1,500 MPa have been selected for both the A-pillar upper reinforcement (thickness 1.7 mm) and the A-pillar upper (thickness 1.1 mm). These components are being laser welded together for a length of 680 mm on each side of the car body.

By utilizing such Ultra High Strength Steel material grades it has been possible to reduce the cross section of the A-pillar with 30 mm compared to the larger XC90 model, which corresponds to a weight saving of 40% or around 5 kilograms. The smaller section improves the driver's bifocal view around the windshield pillar, but in order to enhance this feature even more, the flange which the windscreen is bonded to has been further inclined which makes ordinary spot welding operations impossible as the welding gun can not access such a confined space (**Fig. 11**). Here the only possible solution was to use laser welding.

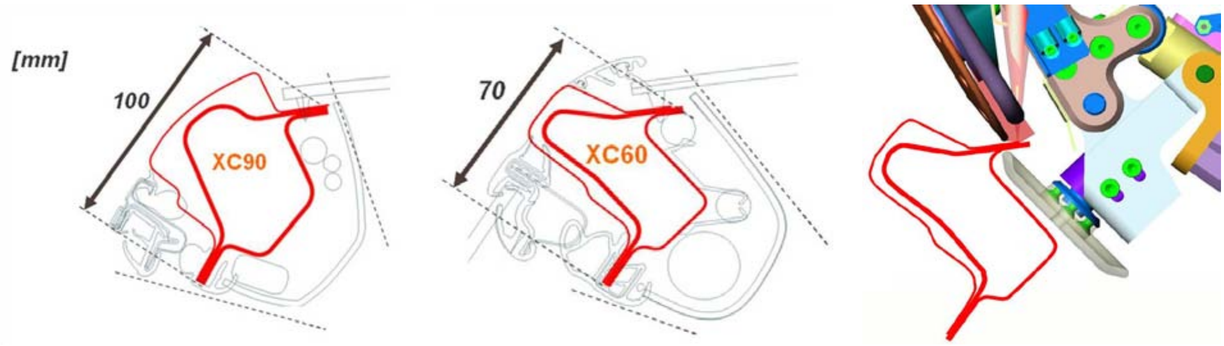


Figure 11. Difference in A-pillar cross section between the XC90 and XC60 models, and at the right the roller clamping device necessary for laser welding.

Another innovative solution addresses the topic of weight savings as today every kilogram saved is a benefit to both customer and society, and a promising example of this is the sill solution of the XC60 model (**Fig. 12**). Also for the sill reinforcement a 1.3 mm thick Boron steel component has been used, which allows down-gauging by 0.7 mm compared to the XC 90 model which features a 2.0 mm thick Dual Phase (DP) 600 steel sill reinforcement. Generally the skin panel of the body side is extended to the lower flange of the sill reinforcement and spot welded to that and the inner part of the sill section through conventional spot welding. In the XC60 solution the outer skin panel is cut some 5 centimeters higher up and meets the sill reinforcement on a flat surface. This permits only single sided access for the joining operation and therefore a laser fillet welding is performed, which consists of two laser welds (531 and 220 mm long) on each side. The overall weight saving from this sill solution is approximately 8 kilograms out of which 1.5 kilograms are saved through the reduced body side.

Figure 12. The solution with a "reduced body side" for the Volvo XC60 which means a weight saving of 1.5 kilograms in comparison to the XC90 design.

An average of ten meters of laser welds will be the scope of new and upcoming Volvo models such as the new S60 and V60 as well as projected small size CUV versions. This large investment in laser technology has only been possible to realize through the extensive research work performed by the VCC Joining Network, as well as the importance of designing the products for laser welding from the very beginning [11]

7 Summary & Future Outlook

This paper clearly demonstrates the necessity of an extensive pre-trial program regarding weldability/assembly of new material grades for the car body structure. Apart from the spot welding and laser activities described here, similar measures are taken for adhesive bonding and mechanical joining techniques like clinching or riveting, the two later are mainly applied to hang-on-parts (HOP) such as doors, hoods, trunk lids and tailgates.

In Europe there is a long term commitment among the automotive manufacturers to reduce the CO_2-emmissions of their products. This will of course put even more pronounced needs for weight reduction and for that reason VCC has a long-term plan how this should be achieved. Without affecting the platform solution there might be another 30 kilograms to save by the implementation of an upper structure consisting of an aluminium roof panel and a load-carrying structure completely made out of UHSS. For further weight savings the underbody, which represents 65% of the overall body mass, must be affected, and new lightweight materials such as aluminium and magnesium will be mixed with different grades of extra high strength steels (EHSS).

Such scenarios will require extensive testing as well as large reconstruction and new lay-outs for the body shops in order to rapidly ramp up the production speed at the launch of a new car model. Apart from the new material scenario that can be expected, such a development also includes the introduction of production methods like hydro-forming, roll-forming, tailored welding blanks (TWB) and patch technology. Also advanced assembly methods like laser scanner welding and cold metal transfer (CMT) arc welding will be the subjects for further investigation in the Joining Network together with other single sided assembly methods such as RIVTAC® technology [12] and single-sided resistance spot welding

8 References

[1] Larsson, J.K., "Stringent Requirements on Safety and Environment make Automotive Car Body Assembly a Challenging Task", *Proceedings Tampere Manufacturing Summit*, Tampere, June 2009

[2] Larsson, J.K., “A Concurrent Approach to Body-in-White Joining Technologies - The Introduction of High Quality, Cost Effective Methods into Running Production” [Keynote], *Proceedings 32nd ISATA Conference,* Vienna, June 1999

[3] Larsson, J.K, Bengtsson, L. and Buchwald, C., "The Join-NET© Data Base - A Body Engineer’s Tool-Box for Information on Joint Properties and Recommendation of Joining Process Parameters", *Proceedings 8th EAEC Conference,* Bratislava, June 2001

[4] Larsson, J.K., Lundgren, J., Asbjörnsson, E. and Andersson, H., "Extensive Introduction of Ultra High Strength Steels Sets New Standards for Welding in the Body Shop", *Proceedings 61st IIW Annual Assembly, Joint Workshop Commission III & SC-Auto*, Graz, July 2008

[5] Larsson, J.K., "Revival of Arc Welding Methods for Body-in-White Assembly - CMT Technology as an Enabler for High Quality & Cost Efficient Solutions", *Proceedings Joining in Automotive Engineering*, Bad Nauheim, April 2009

[6] "Volvos Hochfeste Verbindung", *Blech Magazine, volume 2*, 2010

[7] Larsson, J.K., "Laser Welding and Structural Adhesive Bonding for Body-in-White Assembly – Competing or Complementary Joining Methods?", *The Fabricator Magazine, May issue*, 2007
[8] Larsson, J.K., "Design and Manufacturing Aspects of Boron Alloyed Ultra High Strength Steel Applications", *Proceedings 7th Deutsche Automobilkonferenz "Fügen im Karosserieleichtbau"*, Bad Nauheim, April 2003
[9] Larsson, J.K., "Avoidance of Crack Inducement when Laser Welding Hot-formed Car Body Components – A Variable Analysis", *6th LANE Conference*, Erlangen, September 2010
[10] Larsson, J.K. and Palmquist, N., "Improved Car Body Performance for the Volvo XC60 Model through the Extensive Utilization of Laser Technology", *Proceedings 12th EAEC,* Bratislava, June-July 2009
[11] Larsson, J.K., "Designed for Laser Welding", *Industrial Laser Solutions, May issue*, 2009
[12] www.boelhoff.com