International Symposium on Niobium Microalloyed Sheet Steel for Automotive Application
Edited by S. Hashimoto, S. Jansto, H. Mohrbacher, and F. Siciliano
TMS (The Minerals, Metals & Materials Society), 2006

EXPERIENCE OF JOINING OF HIGH STRENGTH AUTOMOTIVE SHEET IN THE BODY SHOP

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Abstract

In addition to lightweight design, central topics in modern automotive engineering are the continuous optimization of active and passive safety, of corrosion protection and of the general properties in terms of usage and function of the overall vehicle. In order to achieve optimal functionality, economic efficiency and, eventually optimized vehicle weight, the process engineers and design engineers daily face new challenges. Important milestones to achieve these targets are the selective use of new and advanced materials and the provision of proven product,- joining-, testing- and repair processes. In particular the variety of materials expected in the future, once again poses new challenges to the joining and connection technology. Existing joining processes (e.g. resistance welding, shielded arc welding and brazing, laser welding, stud welding, adhesive bonding, self pierce rivet) must be further developed and be supplemented by new process variants. The design of joined components of vehicle structures so that they can achieve required service performance limits without an increase of vehicle weight or cost is of paramount importance to automotive manufacturers. Achieving this goal requires careful selection of, both, steel material and joining technique as well as detailed knowledge of the elastic and plastic behavior of the joined sections, particularly under cyclic loading. This also includes new procedures for the release of new materials and processes from the viewpoint of joining technology. Based on examples of new material and body concepts applied within the BMW Group a report on the results and experience gathered in the application of various joining processes is given.

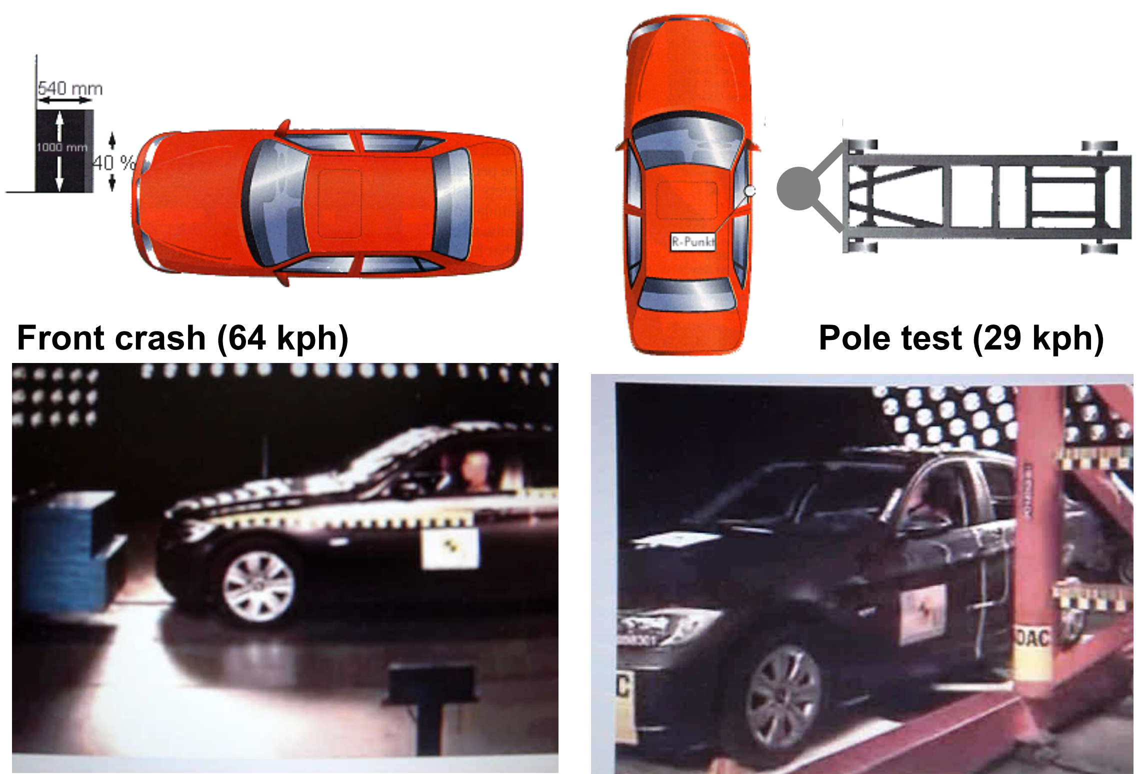
Introduction

Technological development in the Automotive Industry as well as its commercialization caused, among others, the following: Customers more and more associates the properties “light-weight” and ‘fuel-efficient’ with the development standard and attractiveness of a vehicle type. Light weight design thus has commenced to become the central subject of Automotive Engineering, but also of Mechanical Engineering in general. Consequent lightweight design will have benefits there, where energy saving and weight reduction at moved masses can be reached. Therefore light weight design offers excellent chances for product innovation and is essentially characterized by some fundamental approaches. The classic lightweight design approach envisages the application of light materials and high strength to ultra high strength materials. Other approaches prefer the realization of progressive, problem-adapted structures, an exact registration of the strain and stress condition as well as stress-optimized dimensioning. Here distinctions are drawn between material lightweight design, shape light-weight design and concept light weight design. An optimum product design, however, is only reached by a combination of such measures at a justified cost benefit analysis. Therefore lightweight design has to be analyzed and checked at large considering aspects with respect to material engineering, design and production engineering. This is the only means to efficiently tap the existing lightweight design potential and to implement the new materials acc. to their extended capacity. Lightweight design poses a large challenge for the joining technology also. Here it is necessary to extend the performance of the diverse joining methods and supplement these with new processes to fulfill the challenges in regard to new designs and material combinations. Implementation of high strength and higher strength steel material in the body shop require e.g. ductile, strain suitable and safely applicable joins, withstanding the stresses of the lightweight design. For mixed connections (e.g. steel with aluminum) safe and reproducible methods shall be developed and implemented also. Experiences made in the last few years demonstrated that a process chain interdisciplinary examination of the manufacturing process (material, press plant, body shop, surface technology and corrosion technology) is a purposeful and especially mandatory measure. Within this context it has to be considered that the different lightweight design approaches will introduce more complexness in the modern manufacturing process, challenging men (process comprehension) and machine (higher performance) to a great extent. Following, experiences from the joining technology field within the body shop are reported.

Targets and Requirements for Using Multiphase Steel

Figure 1 shows the international NCAP test created for newly developed vehicle bodies. To achieve the requested features - especially in the area of passive and active protection of persons – modern vehicle development is subject to special rules. Hereby the engineer is complied to realize the objectives of ergonomic lightweight design and the optimum on the focus of joinability in addition to the safety aspect.

For this purpose, there are different possibilities. On the one hand conceptual lightweight design is exercised as in the current BMW 5-series with the aluminum front end. While on the other hand lightweight design is executed with shapes based on the hydroforming technique.



ENCAP: European New Car Assessment Program

Figure 1. New car assessment program - High-Strength Steel Body ENCAP Crash Test BMW 3-Series.

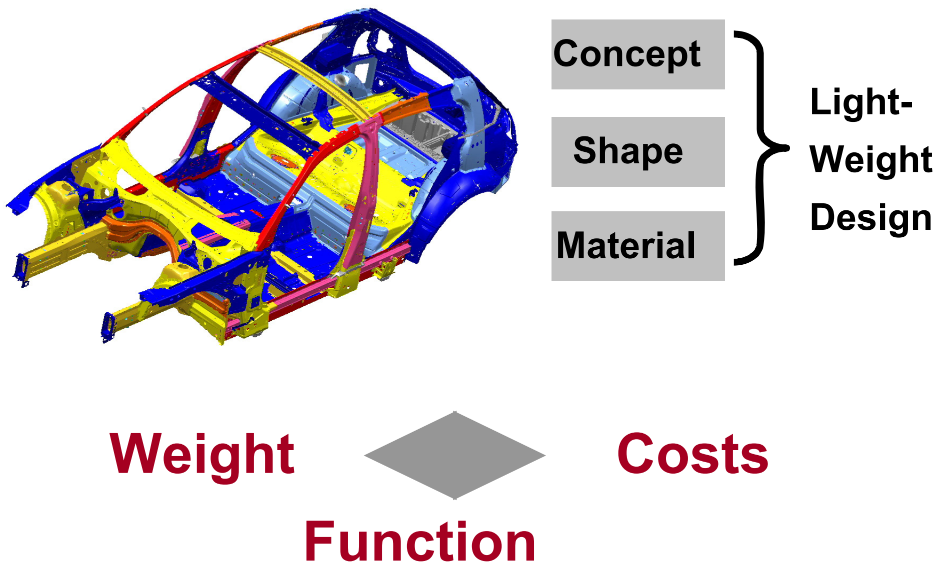


Figure 2. Means to Lightweight Design.

With this option many reinforcement parts can be omitted. With the development of high strength and higher-strength steel materials, at a reduced sheet thickness material lightweight design gains more and more importance. In addition to the functional features and the weight reduction – due to all listed potentials of the light-weight-design - the calculated cost-specifications for a body shall be observed. This poses a challenge for steel and car manufacturers (Figure 2).

Load suitable thin walled sheet materials are provided for each body variant with the aid of certain measures at the manufacturing as well as with intelligent alloy combinations (Figure 3). However, an optimum fulfillment of the functions and weight reduction exists from the material point of view with the disadvantage of a higher complexness due to the multi material implementation (documentation, logistic).

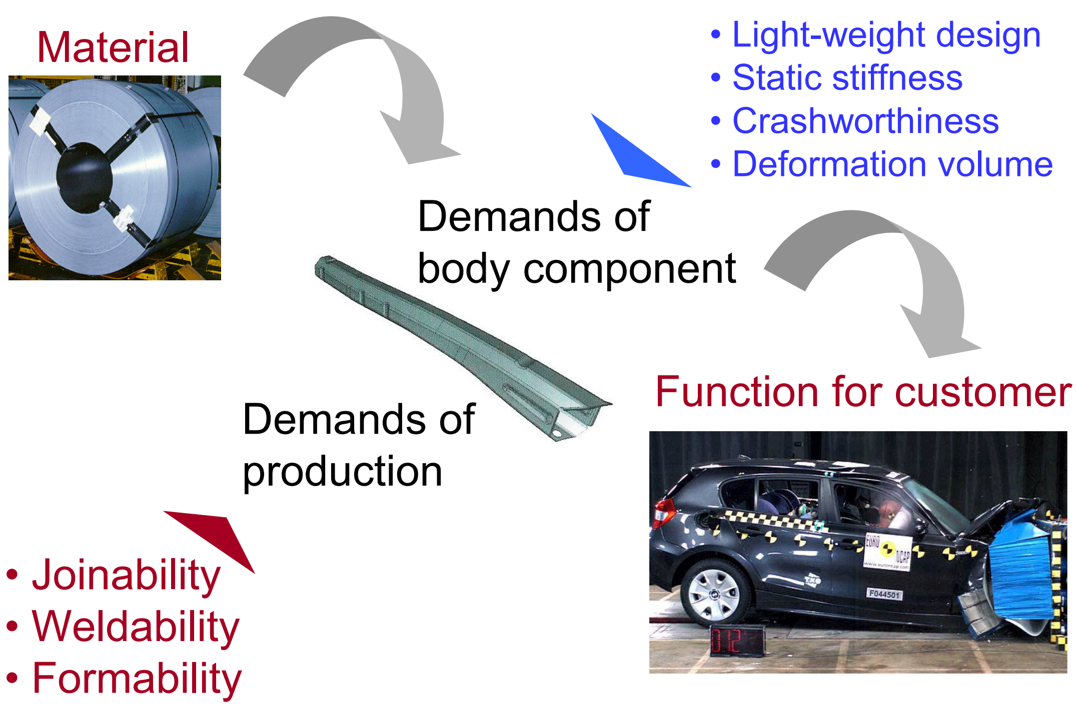


Figure 3. Demands on high strength steel for car body.

Important factors, for example, the weldability and joinability, however, are often under estimated or completely ignored. The ability for repair of new vehicle structures shall be clarified explicitly and shall be assured methodologically.

Steel Sheet Material Use in BMW 3-series

After the clarification of all facts and the solution of all joining related individual questions the optimized high strength and higher strength material implementation was realized for the new BMW 3-series with a proportion of 68 per cent (Figure 4). Here functionally optimized-materials and materials optimized in utilization were implemented with tensile strengths of up to 950 MPa. This is illustrated in the Figure 4 by the different colors of the individual body parts and assembly groups.

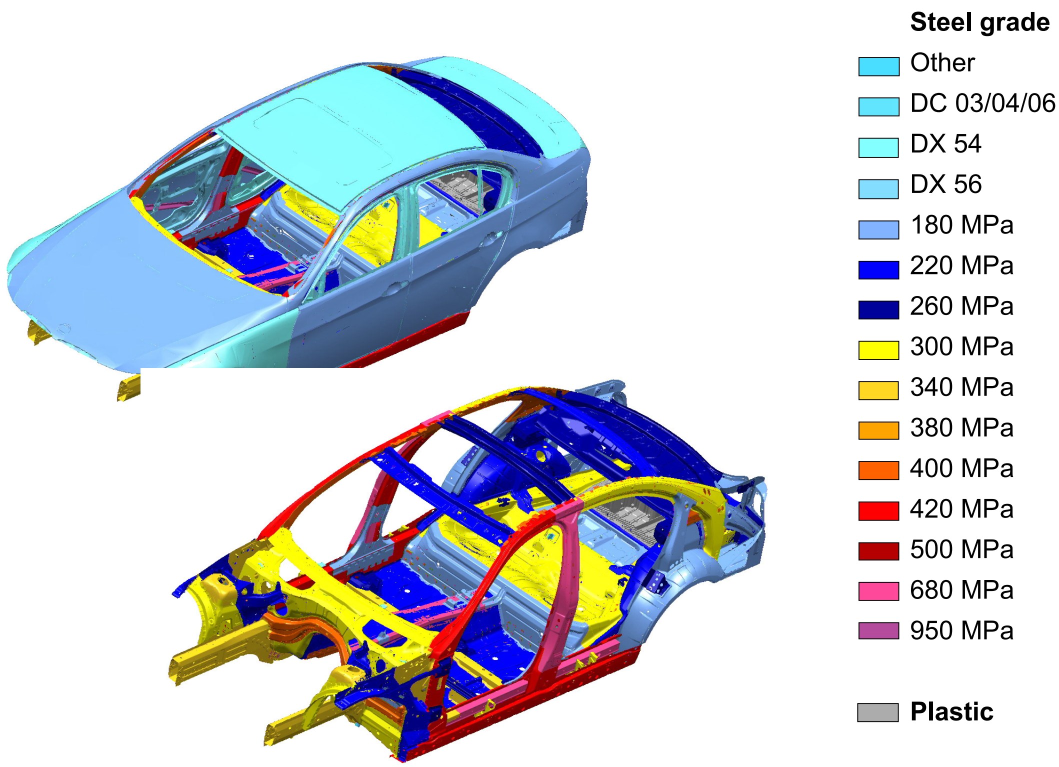
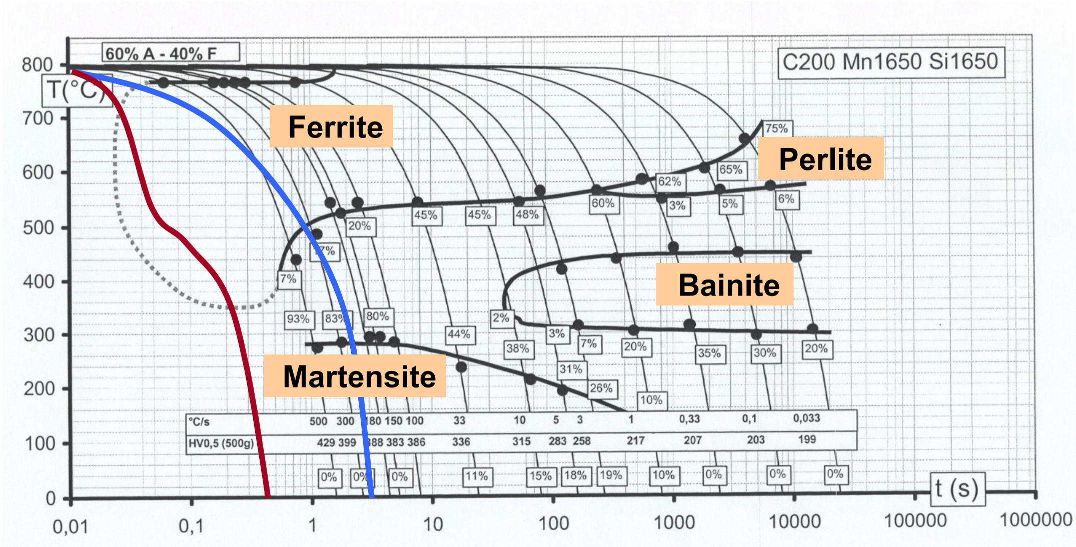


Figure 4. Steel grades used in BMW 3 series.

Proceedings for testing of joint- and weldability

The ability to process and to join materials had to be considered in the early project phase of the new model with respect to the overall process chain "Painted Body". This is an important consideration for joining engineers, since not everything with weldability can be transformed and painted or will meet the function. For the assurance of the welding suitability and the welding process, exact material data sheets and transformation diagrams were requested from the steel manufacturers (Figure 5).

This was the only means to establish a relationship of the present material and the welding results and a way, to comment the results. Accurate procedures for the joining related qualification had to be determined anew. According to the complexness of the material and the joining task process tests upon the test metal sheets were insufficient and had to be complemented by component tests (Figure 6).



C	Si	Mn	P	S	N	B	Cr	MO	Nb	Ni	Ti
0,22	0,036	1,55	0,012	0,001	0,002	0,0004	0,029	0,014	0,005	0,017	0,002

Carbon equivalent (CE) = 0.49

Figure 5. Demands on data-sheets of new materials for assurance of weldability.

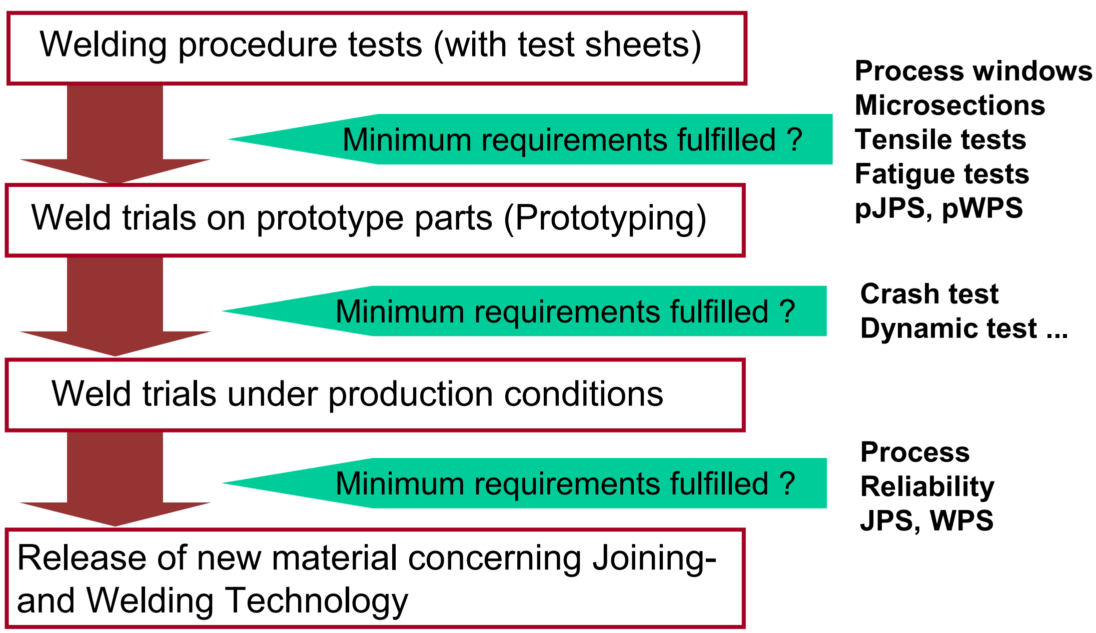


Figure 6. Investigation steps to introduce new materials.

Recently problems in the qualification process of new materials for car body are the different alloying concepts of several suppliers. Frequently new materials with an identical designation, but from different steel manufacturers displayed a varying welding behavior (Figure 7). Depending on the alloy concept, crack free as well as heavy crack afflicted joints are producible. This is an alarming condition in regard to the competitive purchasing of sheet metal materials.

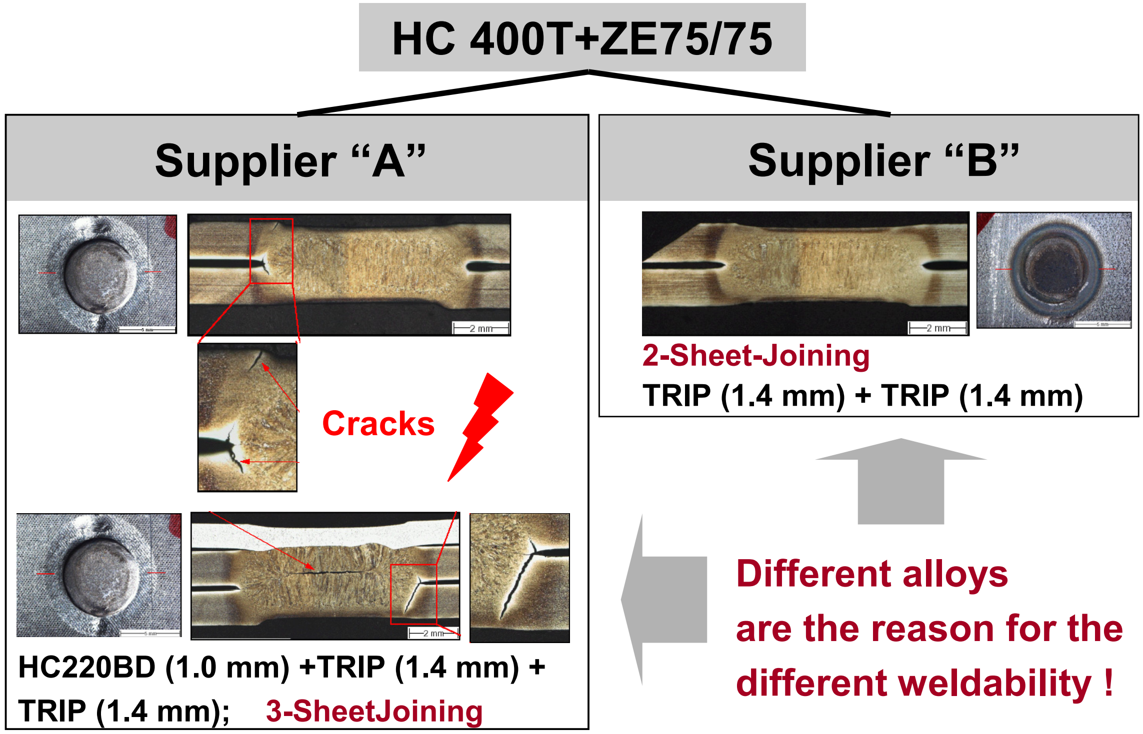
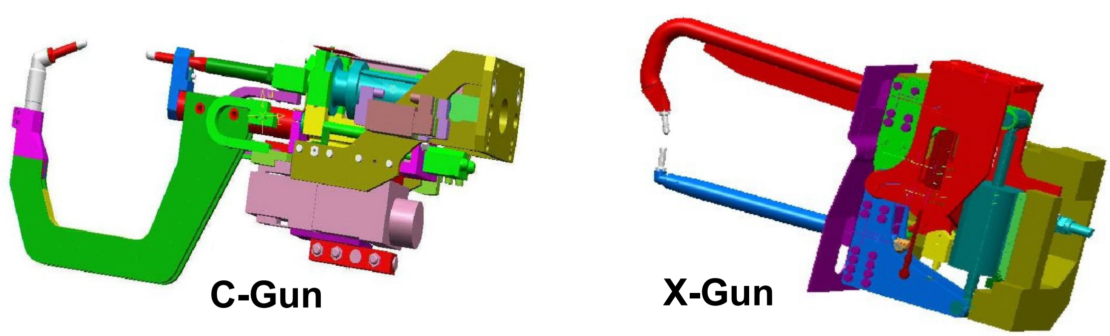


Figure 7. Problem of different alloying concepts of several suppliers.

Effects on joining technologies

Resistance Spot Welding

With up to 5000 weld spots per body, the resistance-spot-welding (Figure 8) is one of the most important and reproducible joining-methods in the body construction. Some characteristics, however, shall be observed at the joining of high strength and higher strength steel metal sheets.



Typical properties:

Available electrode force:	1.6 – 6.0 kN
Available weld current:	up to 22 kA (100 kVA MF transformer) Medium frequency DC
Weld timer:	Bosch weld control with graphical interface, 256 weld programs available

Figure 8. Resistance spot welding: Weld-gun design for volume production.

Thus, for the design of the welding gun geometry it is necessary to allow for the welding force up to 30 per cent higher. During the welding process weld nugget creation due to the resistance build up is favored by the modern mid frequency technology of the transformer. The welding range to achieve the minimum welding spot diameter at a microalloyed high strength steel HC340 LAD – in the thickness-range of 1.2 mm – is in a current range of two kilo ampere (Figure 9).

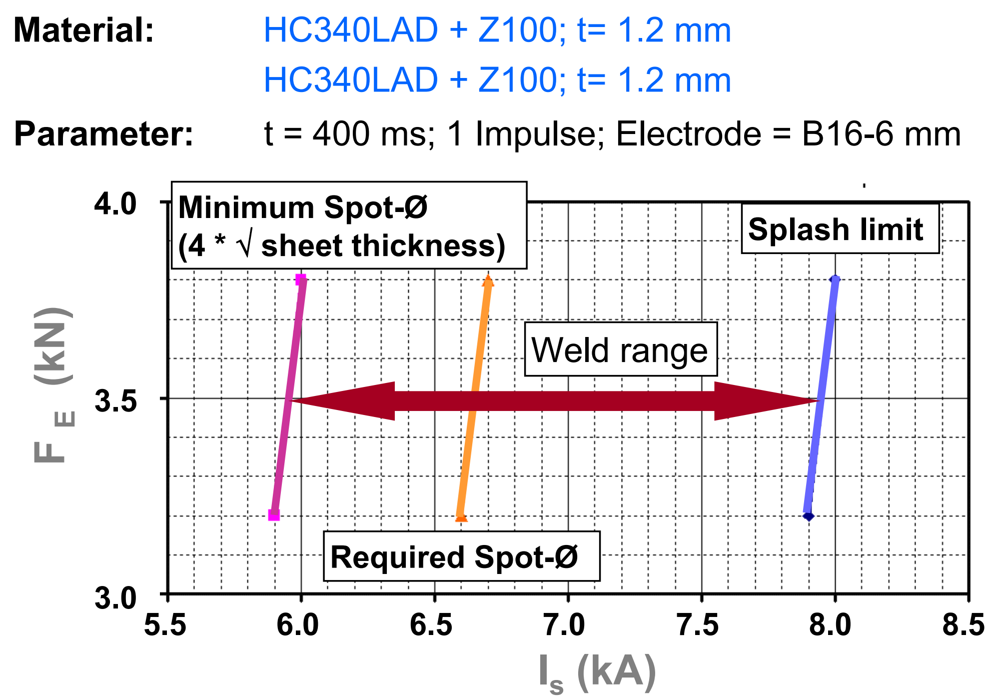


Figure 9. Parameters of resistance spot welding on HC340LAD sheets.

In case of the higher strength HC400 TRIP-steel, in the thickness - range of 1.2 mm - the current range is reduced to 1.5 kilo ampere (Figure 10).

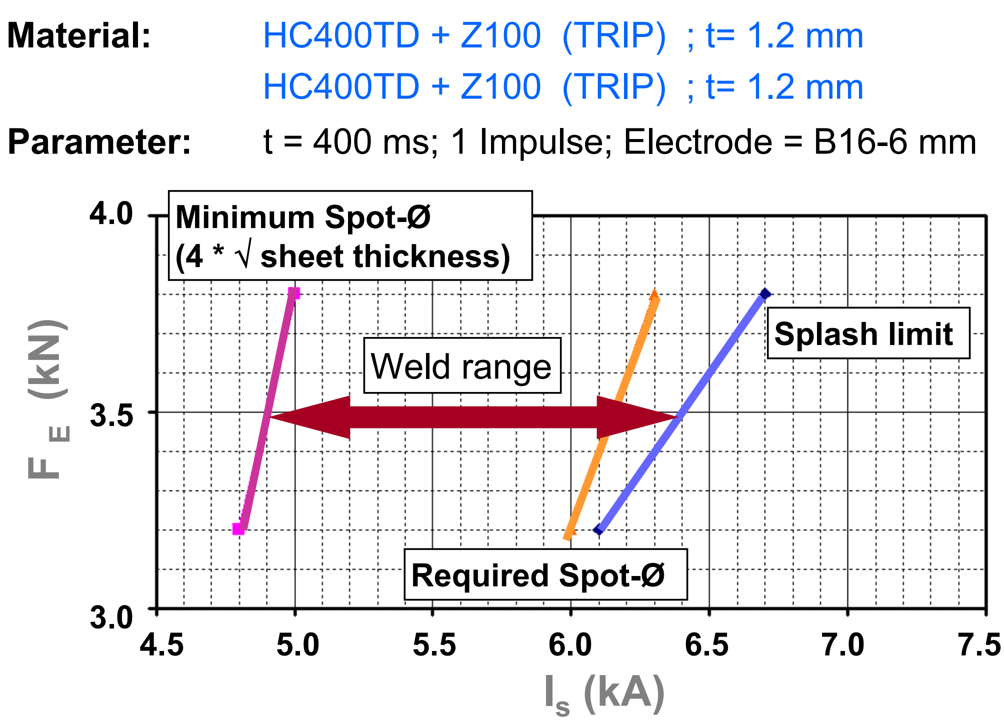


Figure 10. Parameters of resistance spot welding on HC400TRIP sheets.

This means that the process period will become smaller with increasing strength. The welding process reacts more sensitive to disturbances. For compensation and process stabilization purposes, BMW applies an online control at the indicated critical welding tasks (Figure 11).

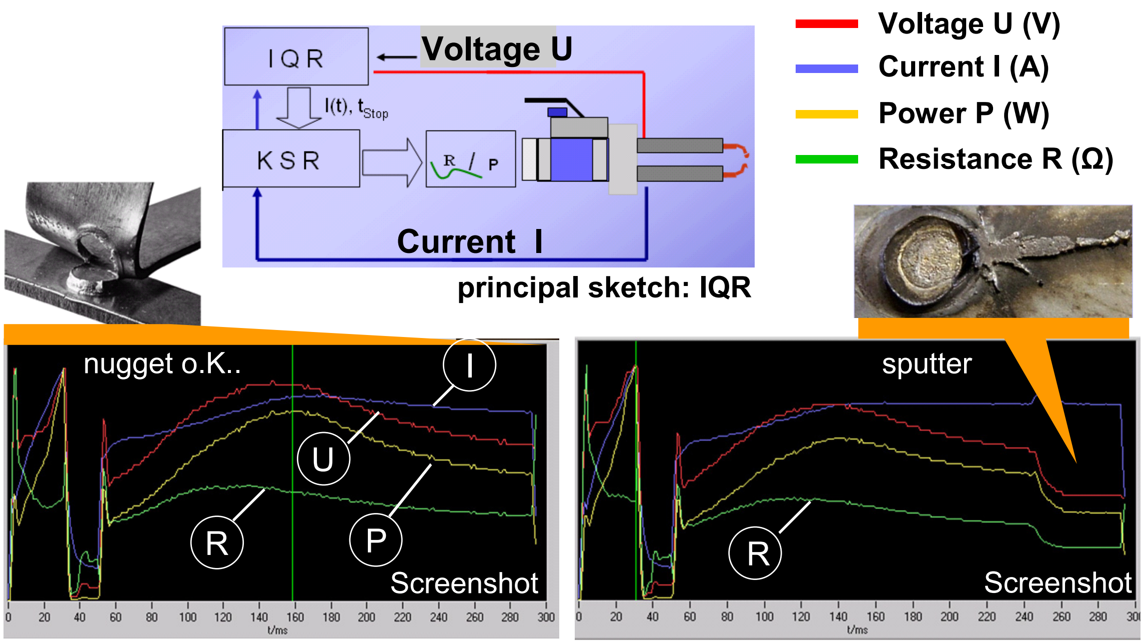


Figure 11. Resistance spot welding online quality control: Process Stabilization by Intelligent Active Online Process Regulation (IQR).

This control actively influences the process settings and controls the welding process in the target corridor for the safe achievement of the required weld spot diameter. Another issue is the risk of material hardness increase in the range of the joining zone and HAZ. At mixed connection, as indicated in the Figure 12, the varying heat conduction of the individual materials may lead to a movement of the weld nugget (position of the resistance heating). This applies to TRIP-steel as shown in Figure 12.

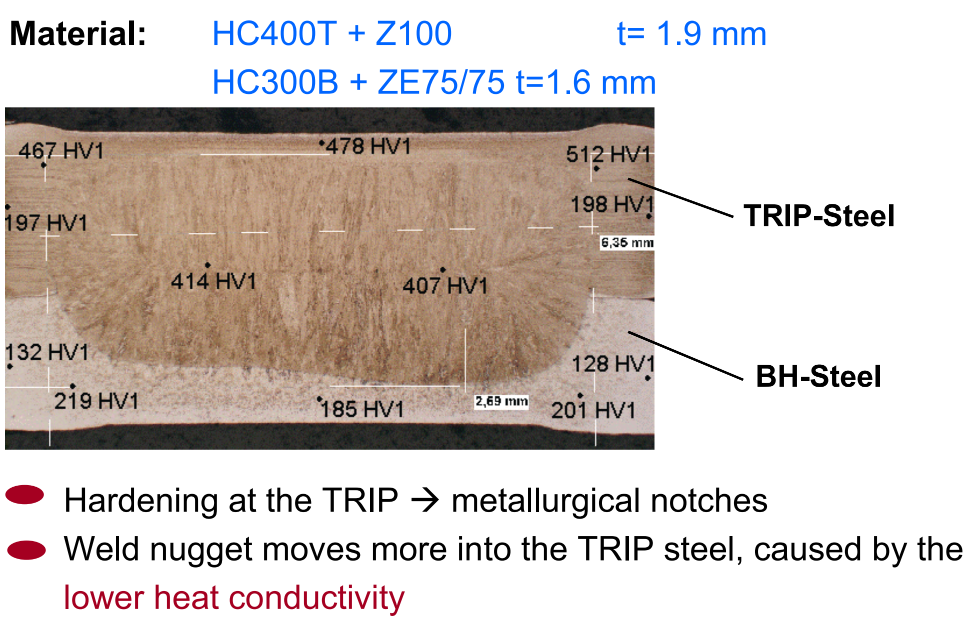


Figure 12. Resistance spot welding: Varying heat conduction on a mixed joint.

Incorrect welding parameters and a wrong welding electrode geometry can also pose problems. The welding result is crack afflicted at the zinc coated dual phase steel of this example (Figure 13).

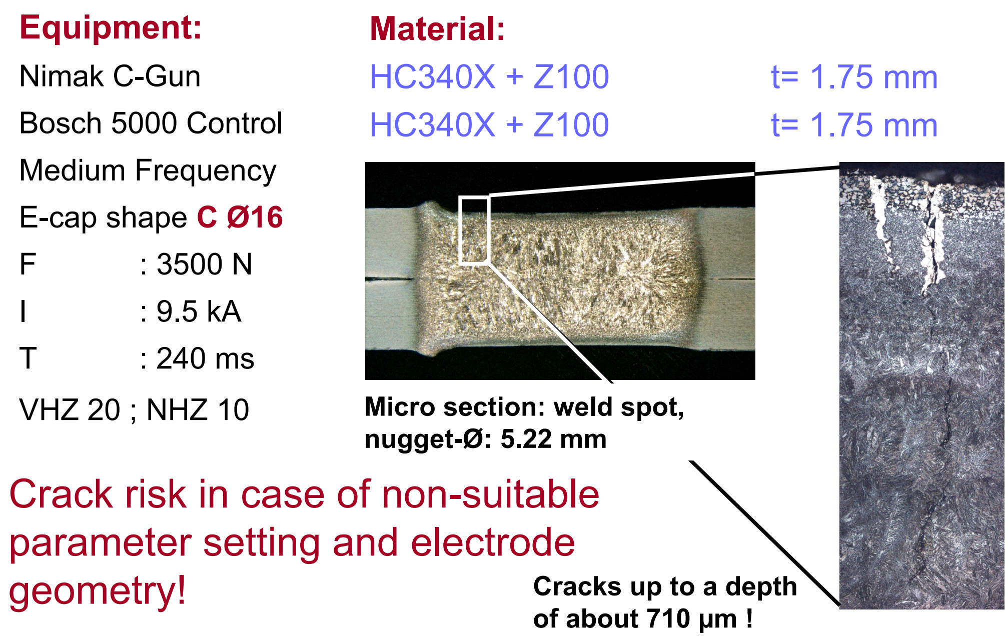


Figure 13. Resistance spot welding: Results of incorrect welding parameters.

Manufacturing with small parameter periods will also require a rethinking in the foreign manufacturing (so-called CKD: completely knocked down); especially in low wage countries at little quantities (Figure 14).

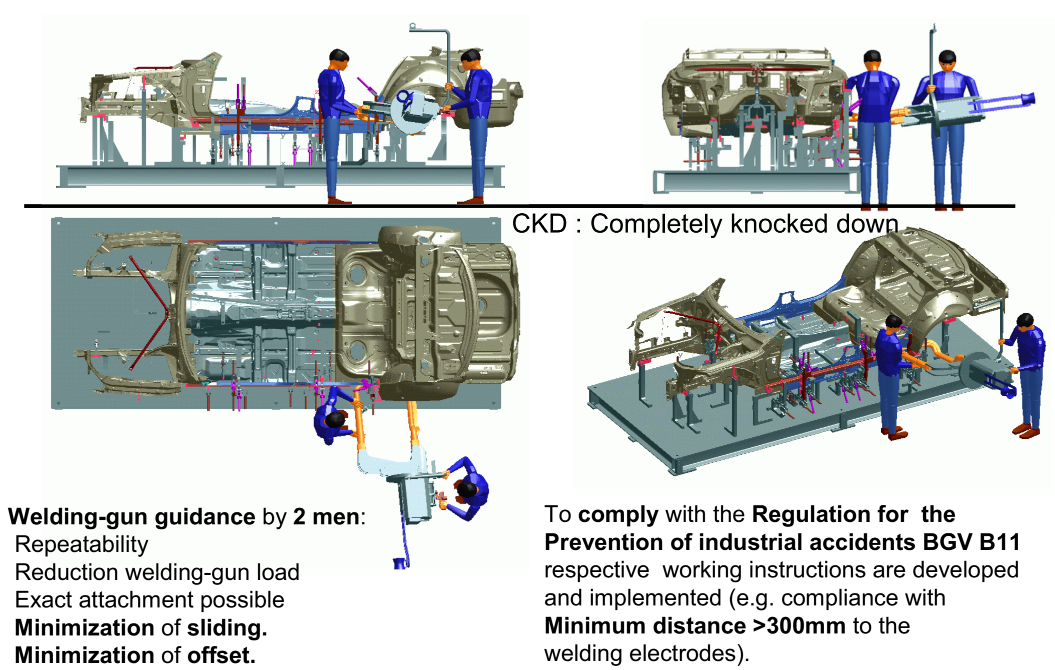


Figure 14. Resistance spot welding: Production concept on CKD market.

The exact application of welding electrodes requires an extra handling effort leading to extra personnel effort or automation by robots. The qualification of the personnel to new situations at joining of high strength steels is an important issue in the qualification chain. The characteristics of resistance spot welding of HSS are once again summarized in the Figure 15. The smaller parameter period is significant at:

- Higher welding gun forces,
- Lower welding currents and
- Longer fusion time.

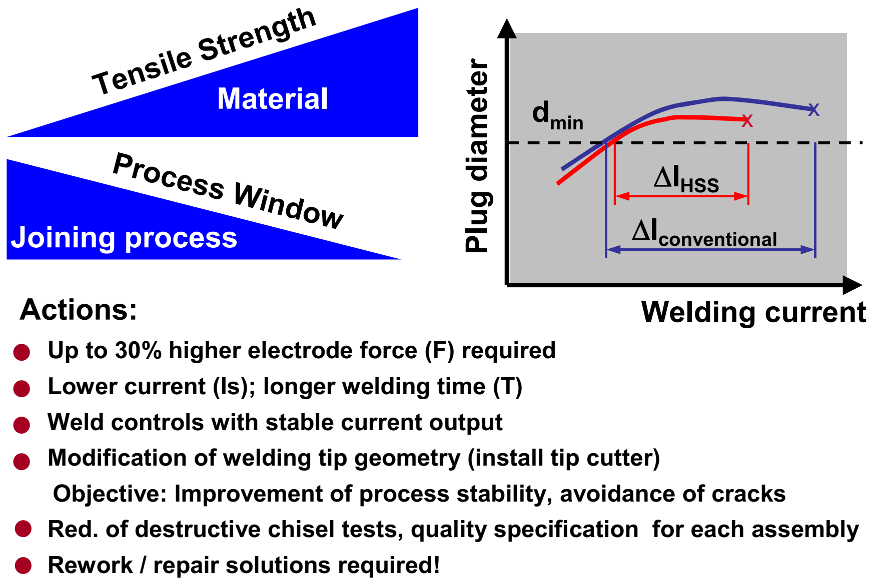


Figure 15. Resistance spot welding: Summary of effects on BIW manufacturing.

Stud welding

With an average of about 300 automatically applied stud-welds the stud welding process is the second most frequently used joining method in the body construction. Compared to stud welding at so-called “mild steels for cold forming”, welding at thin walled HS-Steels are characterized by increased hardness in the HAZ. This is exemplary displayed at TRIP-steel in the graphic in Figure 16.

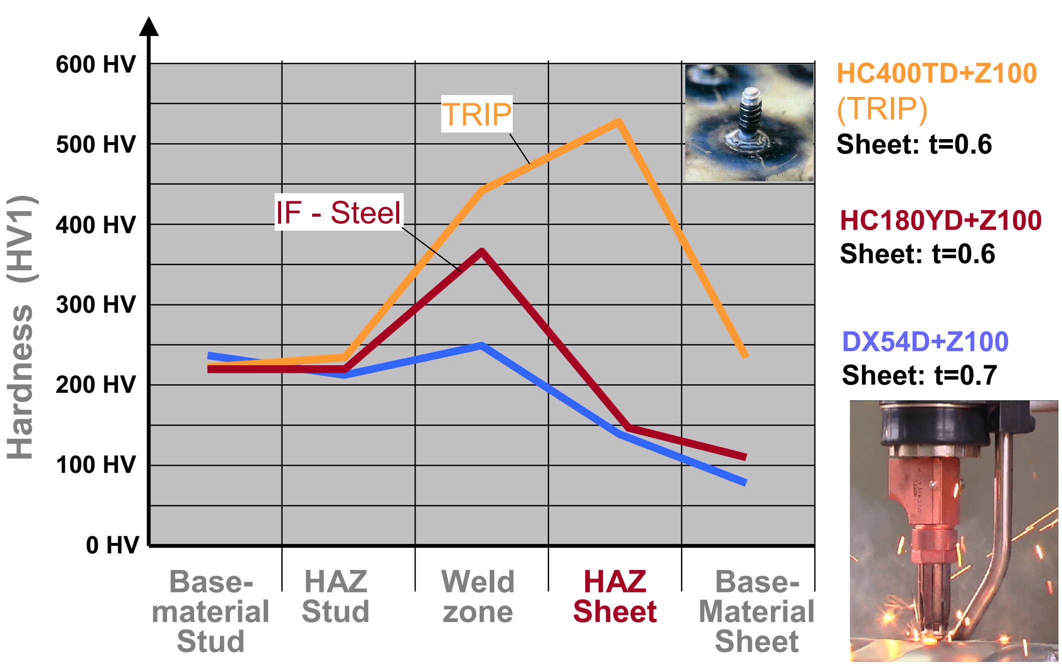


Figure 16. Stud welding: Interrelationship sheet thickness, strength, hardness increase.

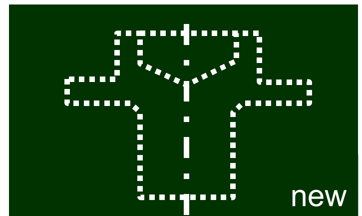
In general at stud welding of HS-Steel a trend towards: shorter fusion times and higher welding currents can be recognized. This is illustrated exemplary with the DX56 compared to the H400 Steel material (Figure 17). For a better control of a heat input, alternatives in the stud design, for example the "wide flange stud" (see picture on left side in Figure 17) and process variants like " stud welding with moved magnetic arc " are processed.

Trend: **Shorter** welding **time** with **higher current**.
Capacity of the power source has to be adapted to these requirements → min. 1500A

Example	0.7mm DX56+Z100	700A / 30ms
	0.7mm H400+Z100	1200A / 14ms

Minimum sheet thickness:
0.7mm (GS 96005-1)

Alternatives to the series- stud:
Magnet arc stud welding
Wide flange stud (WFS)



Weld task: WFS on H400TD + Z100 (TRIP)
Material-Thickness : 0.7 mm
Parameter: : 1700A /18ms
Torque (Mw-3s) : 6.46 Nm
Tensile test (Mw-3s) : 2405 N

Figure 17. Stud welding: Peculiarities, consequences, further development.

Arc- welding and brazing

Electric arc welding is still an important representative process in the joining technology range of car manufacturing (Figure 18).

- Material problems
- Problems on arc welding /brazing
- Effects in BIW production

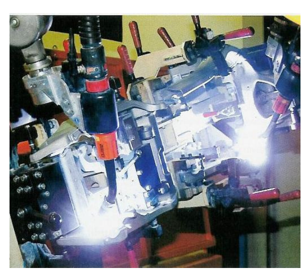


Figure 18. Arc welding / brazing of High-Strength Steel.

Especially the MAG (metal active gas) and MIG (metal inert gas) welding and brazing with filler material is used in the body construction. The applied joining length at the new BMW 3-series amounts to more than 5 meters. An important issue in this subject area is the availability of suitable welding and brazing additives that meet the strength requirements. The fusion point, expansion and tensile strength are the most important filler material characteristics (Figure 19).

	CuSi3	CuAl6Ni2	CuAl8Ni2
Cu	94.0 %	89.3 %	84.7 %
Si	2.95 %		
Sn	0.20 %		
Zn	0.20 %		
Mn	1.30 %	1.60 %	2.30 %
Fe	0.30 %	1.60 %	2.30 %
Ni		1.60 %	2.30 %
Al		5.90 %	8.40 %

	A105M	G3 Si1	G4 Si1
C	0.08	0.12	0.13
Si	0.6	0.10	1.20
P	-	0.02	0.02
S	-	0.02	0.02
Mn	1.7	1.60	1.90
Cr	0.2	-	-
Ni	1.5	-	-
Mo	0.5	-	-

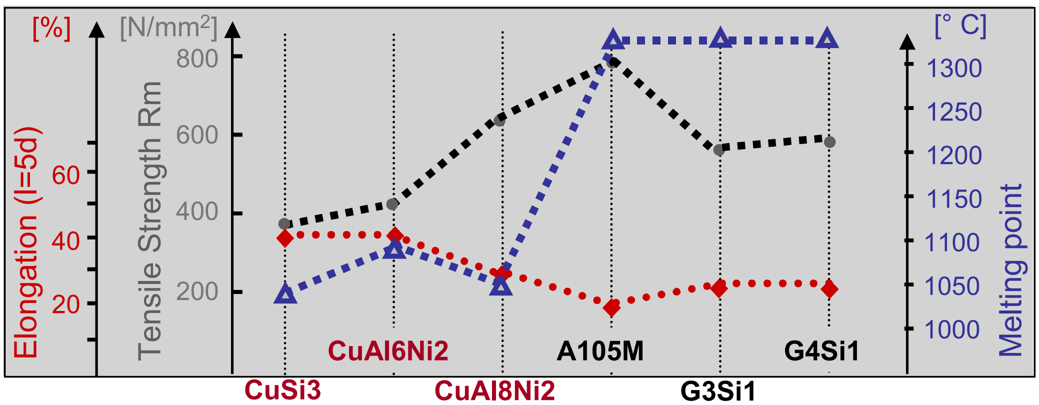


Figure 19. Arc welding / brazing: Characteristics of filler wire base material.

A good example for this purpose is the welding in the B-post area at higher strength case hardening steels in the side impact area of the vehicle structure (Figure 20).

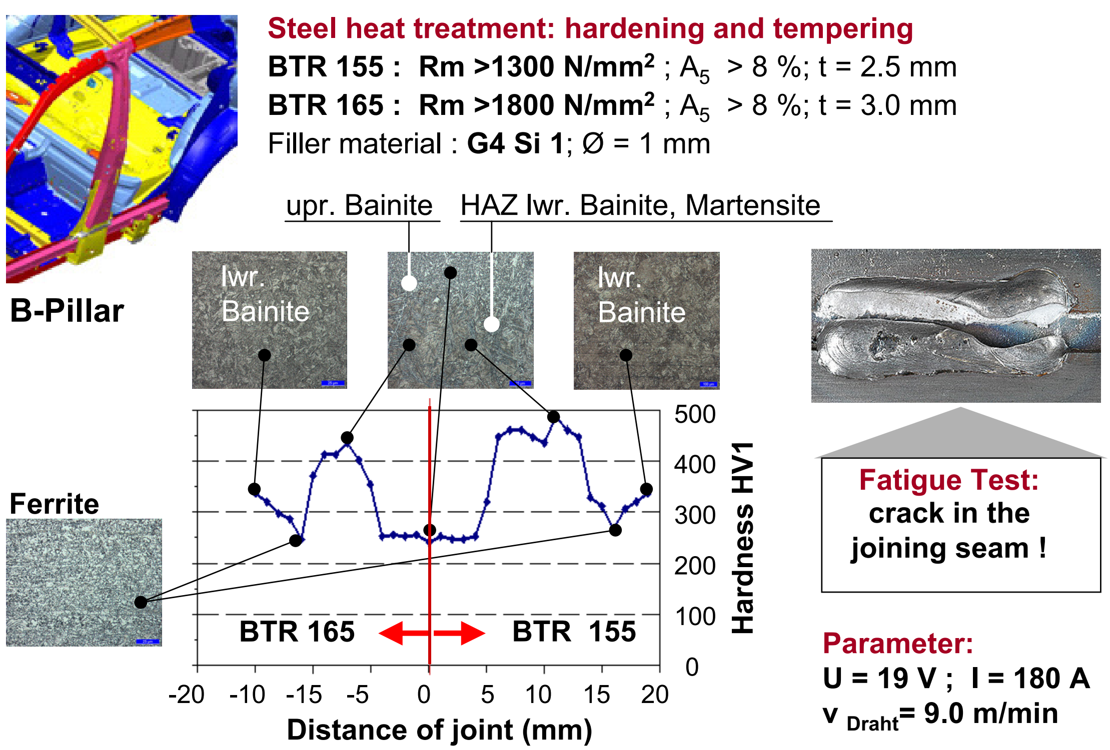


Figure 20. Arc welding: Welding results on BTR-steel.

The arc-weld-process with the higher strength additive G4Si1 was selected due to joining tolerance reasons (gap width up to 1.5 mm) and applicability and accessibility reasons. The weakest link in the force path is the seam itself, as proven in the fatigue test, shown in the picture in the right (Figure 20). Metal inert gas brazing is used where the ductility of the joint is superordinated to the strength of the joint (Figure 21). Especially at brazing of thin walled HS-steels, problems of crack formation in the HAZ shall be considered and shall be avoided with the aid of a dosed controlled heat input. There is still a demand for development in the provision of filler wire with higher strength and Braze material properties.

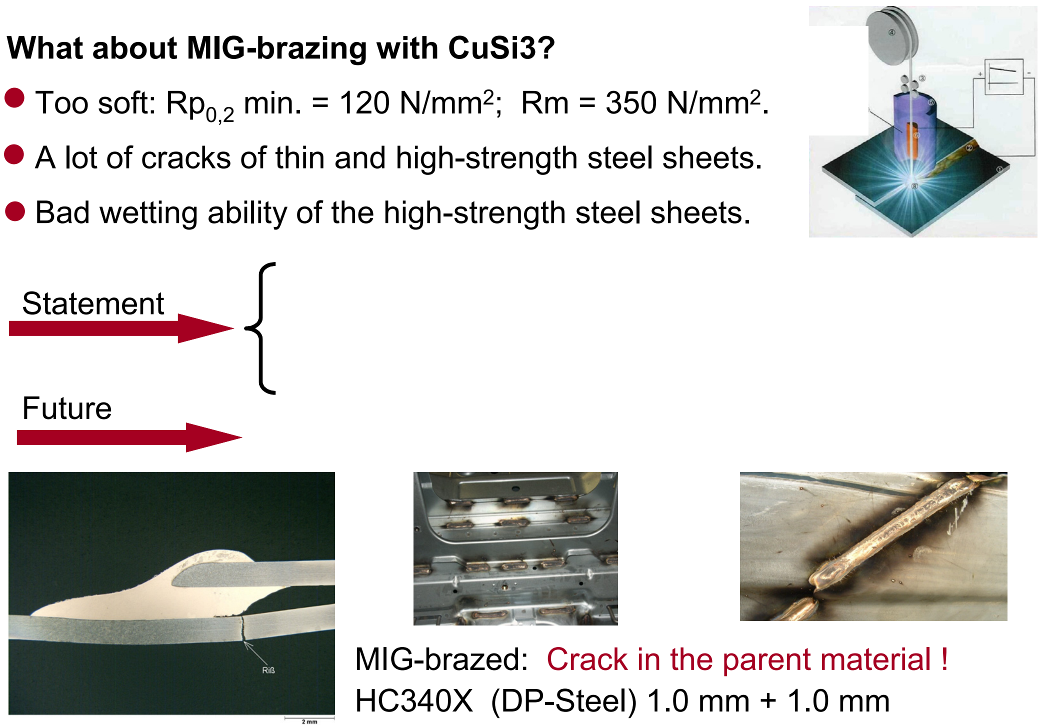


Figure 21. MIG (metal inert gas) brazing, results.

<u>Self pierce rivet technology</u>

An important issue in the constructive light weight design is the joining of different light weight design materials, for example aluminum and steel. Here self-pierce riveting is an often-used joining process (Figure 22).

This joining method is applied more than 600 times at the current BMW 5 and 6-series. Joints of 3-metal-sheets are also possible, as described in the lower right-hand picture in Figure 22. For the joining of mixed joints with HS-steels, 20% higher Joining gun forces are required as well as modified rivets (Figure 23). Further development at the tooling (drive concept) and the joining element (the rivet himself) are required.

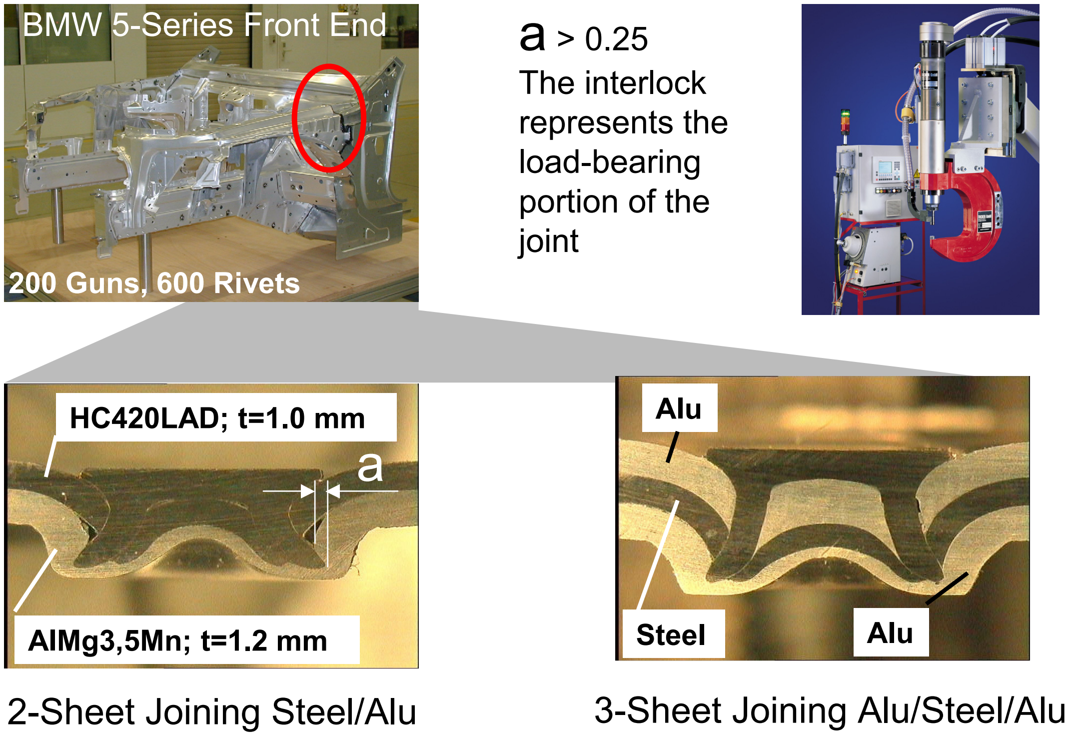


Figure 22. Self pierce rivet technology: State of the art.

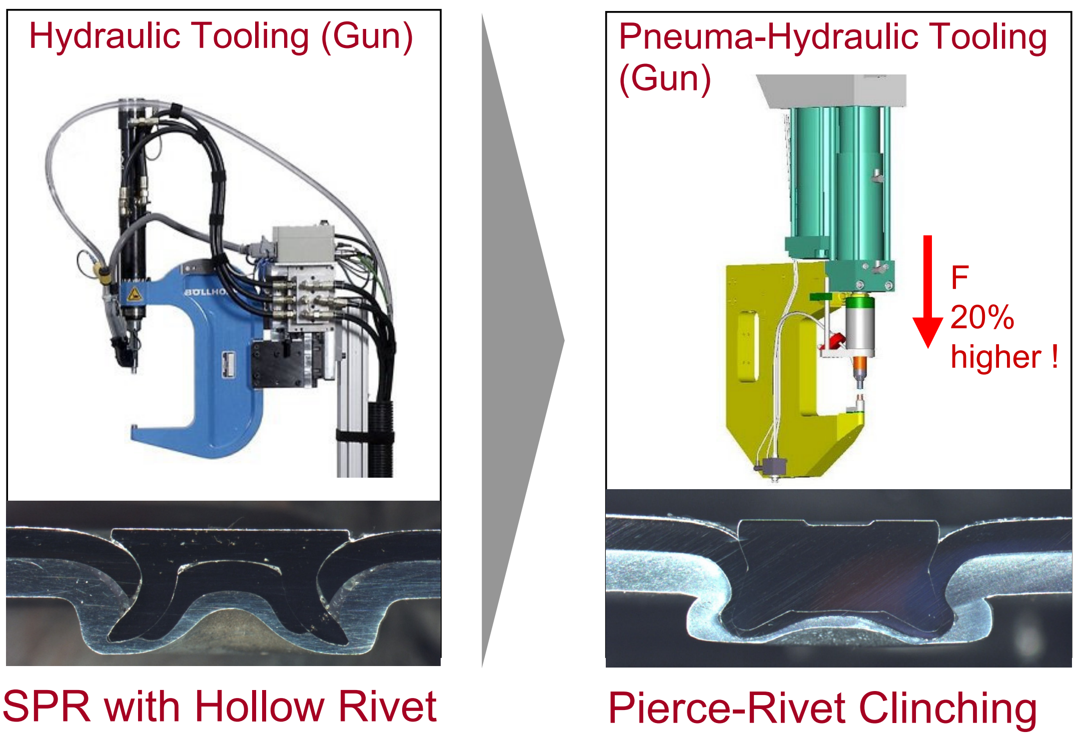


Figure 23. Self pierce rivet technology: Further development of guns.

Since “common” hollow rivets (shape C) are too soft and since an excessive spread ratio leads to inadmissible cracks, rivets with a higher strength (hardness grade 4) and adjusted geometry (shape P, refer to picture on the lower right) shall be provided (Figure 24).

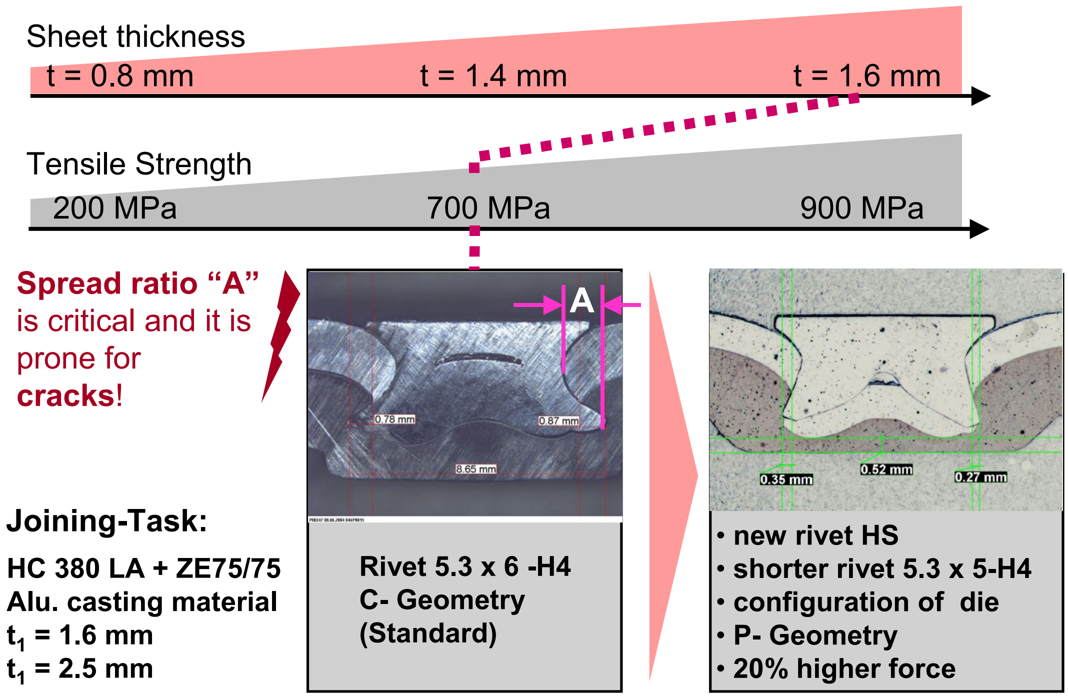


Figure 24. Self pierce rivet technology: Further development of rivets.

<u>Adhesive bonding</u>

An interesting approach in this context is joining by even adhesion of shells (Figure 25). This applies especially to material pairs at which the fusion weld is difficult and where the material pairs are characterized by excessive hardness increase from the metallurgy point of view. With the aid of the sandwich effect higher component rigidities can be achieved at the bonded structures. Refer to Figure 26.

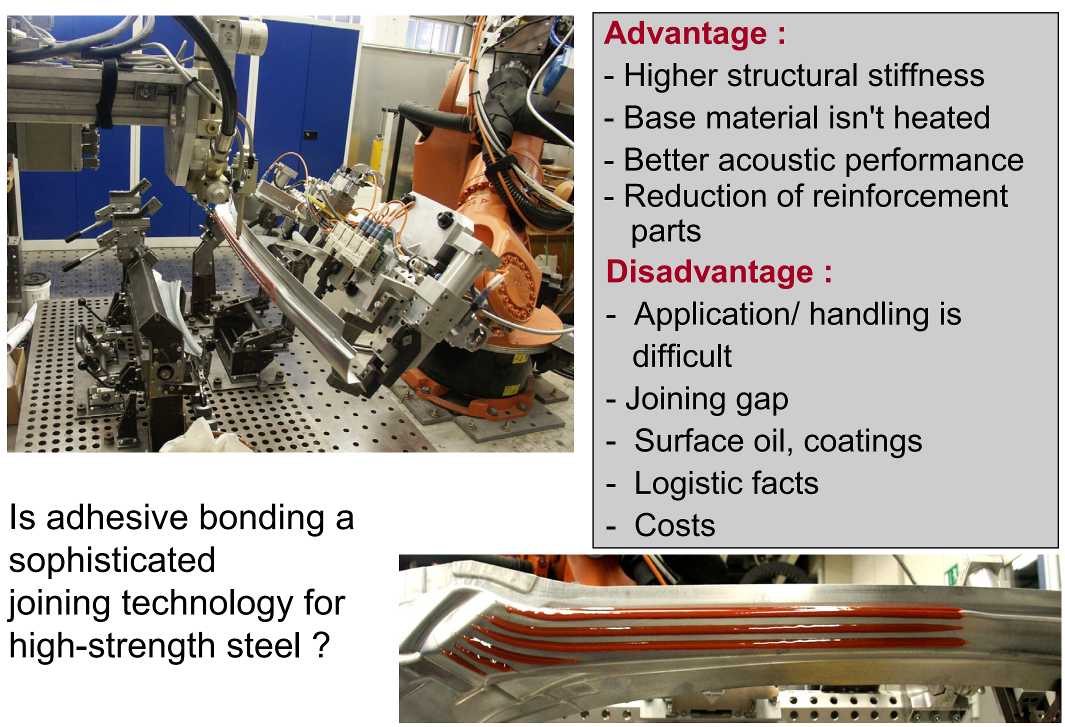


Figure 25. Adhesive bonding in the BIW production.

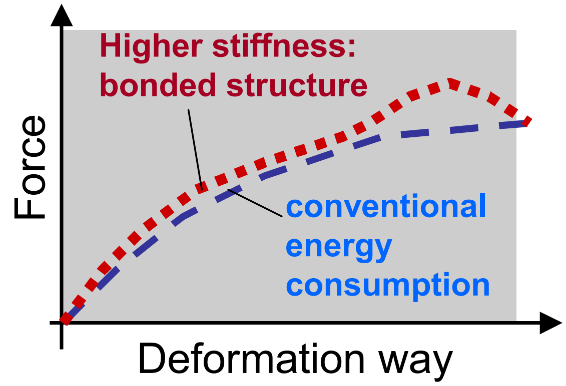


Figure 26. Adhesive bonding: Increasing rigidity of bonded structures.

In addition to those advantages the bonding technology is characterized by a certain complexness in the application technique. The requirements upon bonded gaps of up to few tenths of a millimeter have to be managed from the component-side. The adhesion behavior of adhesives – at coated steel sheets – is a constantly to be verified question. In addition to a controlled logistics – in the sense of adhesive open periods of the adhesive box – the relatively high costs for adhesives at the planned applications shall also be observed.

Laser beam welding and brazing

Laser-beam-welding and brazing are more and more used in the car manufacturing. Narrow weld seams, fast process speeds and a one-way accessibility only to the joining task are impressive reasons for this process (Figure 27). As heat source gas- (CO2), solid-state- and brand new the disk-laser, with a power range of 2000 to 8000 W are applied.

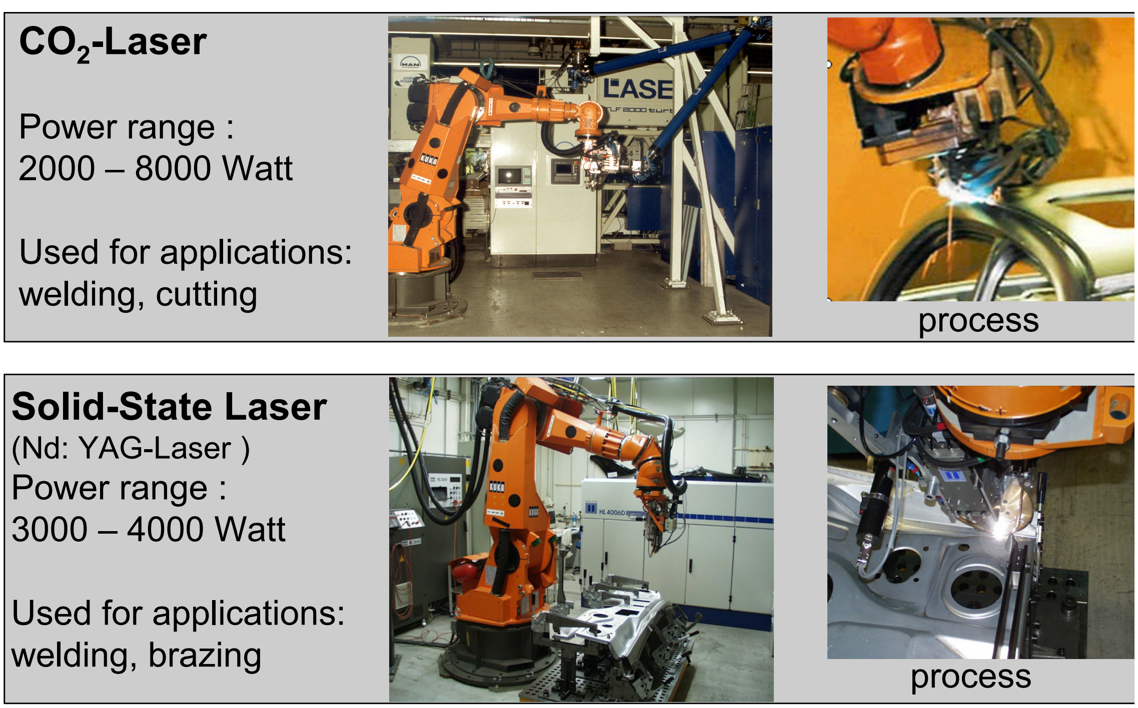
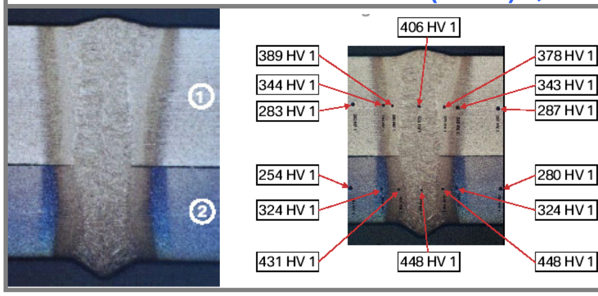


Figure 27. Laser beam joining of high strength steel.

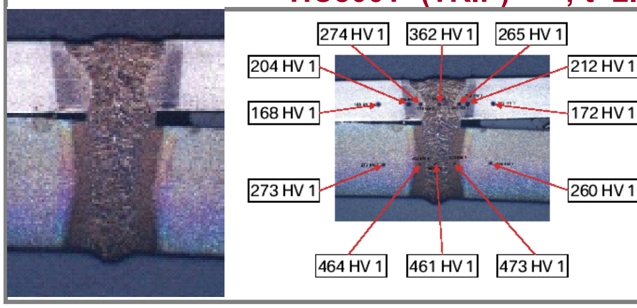
Due to the small, but very concentrated heat application (low heat input per unit length of the weld) the hardness increase behavior at the different material pairs especially at HS-Steels shall be observed (Figure 28). The degree of hardness of up to and above 500 degree Vickers may strongly influence the ductility of the joint.

Material: **SD800C (CP) ; t= 3.0 mm**
HC800T (TRIP) ; t= 2.0 mm



Laser power	= 5 KW
Progress speed	= 2.0 m/min
Roll pressure	= 250 N
Focus position	= ± 0
Focal length	= 240 mm
Shield gas	= He 20 l/min

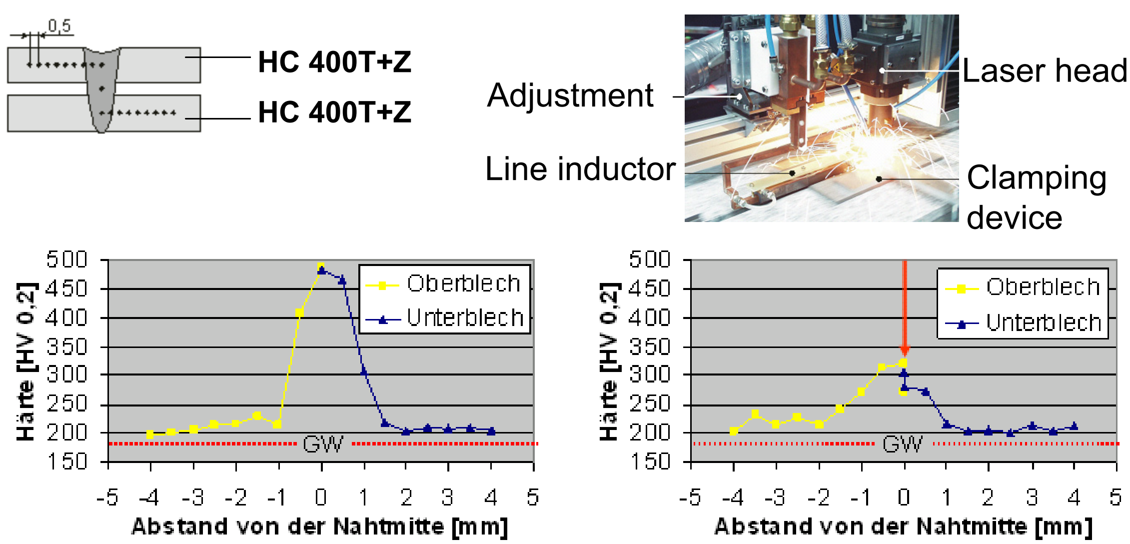
Material: **HC420LAD Z100 ; t= 1.2 mm**
HC800T (TRIP) ; t=2.0 mm



Laser power	= 5 KW
Progress speed	= 3 m/min
Roll pressure	= 250 N
Focus position	= ± 0
Focal length	= 240 mm
Shield gas	= He 20 l/min

Figure 28. Laser beam welding: Examples of cross sections on HSS.

In a sponsored research project the pre heating effect by means of inductive preheating at TRIP-steels was investigated. With a preheating inductor performance of 14 kW a reduction of hardness increase in the weld seam and basic material can be achieved, as shown in the graphic on the right page (Figure 29). This effect was proven at further material pairs with different Carbon Equivalents (CE). The results are shown in Figure 30. How far preheating in practice is feasible, considering the space critical considerations at 3-dimensional components shall be verified from case to case.

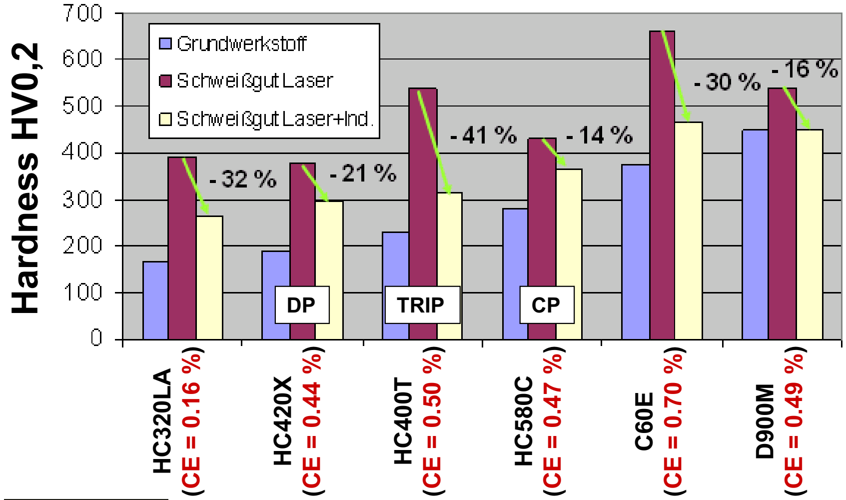


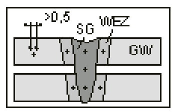
Cover sheet	**: HC400T +Z; 1.5mm**
Gap	**: 0.2 mm**
Lower sheet	**. HC400T +Z; 1.5 mm**
Laser power	**: 400 Watt**
Welding speed	**: 3.5 m/min**

Material + parameter as left side

Inductor power	**: 14 kW**
Distance/gap	**: 1.5 mm**
Welding speed	**: 4.2 m/min**

Figure 29. Laser beam welding: Preheating effects on weld metal.





$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \quad \text{(nach IIW)}$$

Figure 30. Laser beam welding: Preheating effects on weld metal.

Summary - Joining of High Strength Automotive Steel Sheets

Spot welding	:	comparable results considering the boundary conditions
Shielded-arc welding	:	mixed joints weldable with standard conditions; HSS to HSS weldable with suitable wire and gas
Stud welding	:	comparable results
Laser-beam welding	:	comparable results (zinc evaporation)
MIG-brazing	:	at present not applicable (filler is too soft)
Self-pierce rivets	:	standard rivets not applicable
Adhesive bonding	:	comparable results, but pay attention on coatings (danger for lack of fusion)

- Hot joining technologies → hardening in the HAZ
- Each joining situation has to be checked in regard to the risk of cracks and in the demand of the product.

Figure 31. Summary - Joining of high strength automotive steel sheets.

The paper has shown that the implementation of high strength and higher strength steel in the modern vehicle construction can contribute to the safe design and to light weight design. With regard to the joining-technologies – as an essential contribution to the functionality of newly dimensioned structures – restraints in the applicability and the potential of the different processes will be experienced. This means: A systematic assurance and further development of the varying joining processes to the new situations is compulsory. At the hot joining processes the risk of hardness increase in the HAZ and in the weld metal shall always be considered. At BMW the results are consolidated in joining-technical-databases and provided to the design- and production-engineers.