A review of laser welding technology for mass production of tailored blanks

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Abstract

Laser welded steel blanks have made a remarkable career from rather infrequent applications at the end of the 1980's to an indispensable product in today's and future automotive body design. Within a decade, the design of laser welded blanks has evolved from very simple to rather complex layouts in order to comply with the continuously increasing challenges of weight reduction, engineering properties and cost. Over the same period of time, the various players in the market have developed many different laser welding production concepts and related sub-technologies. Meanwhile, some of them have already proved to be dead end roads. Only those allowing to make a superior product in terms of cost, quality and flexibility can survive in this highly competitive market.

The review starts from the basic principle of keyhole welding working out the major requirements for the laser source beam delivery and focusing optics. The forthcoming implications concerning welding speed and seam properties are explained. Thereafter material flow and handling technology is discussed to identify specific characteristics in view of productivity and flexibility. Cycle time, manufacturing constraints and, thus, cost effects will be analysed on the example of typical blank designs demanded by the automotive industry. Finally recent procedures of weld quality control are updated and will be discussed with respect to customer requirements. The synthesis of all these elements finally tries to project the further evolution of laser welded blank technology.

Keywords: laser welding, tailored blank, lightweight vehicles

1 Challenges to modern automotive body engineering

The beginnings of the all-steel automotive body dates back to 1912 when Edward G. Budd introduced this novel concept to the industry. Quickly steel became the dominant construction material for vehicle bodies and remained unthreatend for many decades. The oil crisis in the seventies as well as upcoming safety standards forced the automotive industry to develop improved body concepts offering reduced mass and simultaneously a higher overall stiffness. These challenges led to escalating manufacturing costs while the sector has been confronted with increasing global competition. As a consequence, the established position of steel as body construction material became threatened by lightweight materials such as aluminium, plastics, and magnesium. The disadvantage of higher density of steel, however, can be compensated for a good part by its higher stiffness, strength, and durability as compared to many lightweight materials. Thus, the competitive position of steel could be regained by creating new semi-products tailored to the specific application. Tailor welded blanks have become a key product in lightweight body construction to meet the increased challenges at acceptable cost.

2 Market evolution of tailor welded blanks

Tailor welded steel blanks have made a remarkable career from rather infrequent applications at the end of the 1980's to an indispensable product in today's and future automotive body design. Within a decade, the design of laser welded blanks has evolved from very simple two sheet combinations towards rather complex sheet puzzles. The driving forces for this rapid evolution is based on:

- Weight reduction
- Advanced crash management
- Enhanced structural integrity
- Cost reduction by part integration and more efficient material use.

2.1 The early years

The idea of tailor welded blanks is actually not that young. Already in 1964, the Budd Company filed a respective patent and since 1968 truck frame members were being produced in the USA by A.O. Smith by means of elctron beam welding. In 1979 Volvo introduced a first welded blank application in Europe using resistance mash seam welding. Later, Volvo developed an induction butt welding process to enhance the design possibilities and to make production more efficient. In the early 1980's laser welding appeared as an interesting alternative due to its low heat input and high welding speed. At the end of the decade resistance mash seam welding was still the dominating production method. However, laser butt-welding continued its evolution to become the preferred production technology since 1995.

2.2 Industrial break-through

The supplier base of tailor welded blanks was initially rather limited. On the one hand side, some automotive companies such as Volvo, Toyota and Renault produced in-house for their own needs. In Europe, few steel companies started to offer this product on a limited scale to interested automotive customers while in the USA the same was done by independent service centres. In the beginning of the 1990s, many automotive companies were still sceptical about the use of tailor welded blanks with exception of Volkswagen who introduced them in high volume for its Golf III model launched in 1991. Although these blanks were mainly produced by resistance mash seam welding, the strategy of the same company to make increased use of fully galvanised steel sheet indicated the limitations of mash seam welding. In this early phase of an evolving supplier market, Sidmar decided in 1994 to start up a production facility (Tailor Steel) exclusively using laser butt welding technology. By the end of the 1990s laser welded blanks have become common sense in the construction of modern cars. Each recent vehicle contains in the average four laser welded blank applications. Due to this market explosion, most European flat steel producers have installed production facilities by now; almost all of them based on laser butt welding technology. Beyond pure economical reasoning, the entrance into the laser welding business was for many steel companies also a matter of prestige giving a flavour of high tech to an industry that is commonly looked at as "old economy".

3 Laser butt welding process implications

3.1 General process conditions

Laser butt welding of steel sheets makes use of the so-called keyhole welding process. In this process, the laser radiation is focused to a small spot of extremely high intensity. Material in the irradiated area is instantaneously evaporated and a vapour channel commonly known as keyhole is formed into the depth. The welding process relies then on a continuous displacement of the keyhole along the joining line. The material is melting around the keyhole and solidifying immediately after the keyhole has passed to form an autogenous weld. The heat-affected zone has thereby a high depth-to-width ratio rendering only a very small volume material with altered properties. The intensity of laser radiation in the focal plane as well as the mean gage of the steel sheets to be welded determines the maximum achievable welding speed. Since the focal plane diameter is bound by a lower limit typically not less than 0.3 mm, the average intensity and, thus, the welding speed at a given mean gage can only be increased by using higher laser power (Fig. 1). In the early days of laser butt welding, CO2 laser of 4 to 5 kW maximum power set the limits. Today, CO2 lasers of the 8 kW class are the workhorses of the industry. In exceptional cases, CO2 lasers of the 12 kW class are used to further increase the welding speed particularly at increased sheet gages.

There is also an upper limit to the intensity above which plasma shielding effectively blocks off the transmittance of CO2 laser radiation to the work piece. Therefore it is important to avoid local intensity peaks within the focal plane especially when using laser of 8 kW or more power. A former sales argument of laser manufactures, namely to strive for high beam quality and thus good focusability is not strictly valid anymore for today's high power CO2 lasers. Less attention has been paid so far to the depth of focus, which controls the energy concentration in the direction normal to the focus plane. Because of the limited thickness of automotive steel sheet, the depth of focus should not be much larger than the sheet gage to obtain a good coupling of the laser energy. This effect can be experimentally verified by defining the process efficiency as being the volume of fused metal per irradiated energy. The laser welding process becomes most efficient when the depth of focus is nearly identical to the sheet gage (Fig. 2). For a given beam quality and focusing optics maximum possible process efficiency depends only on the sheet gages to be welded. An inferior process efficiency is typically caused by energy losses due to through gap transmission, surface reflection, or plasma shielding of the incident laser radiation.

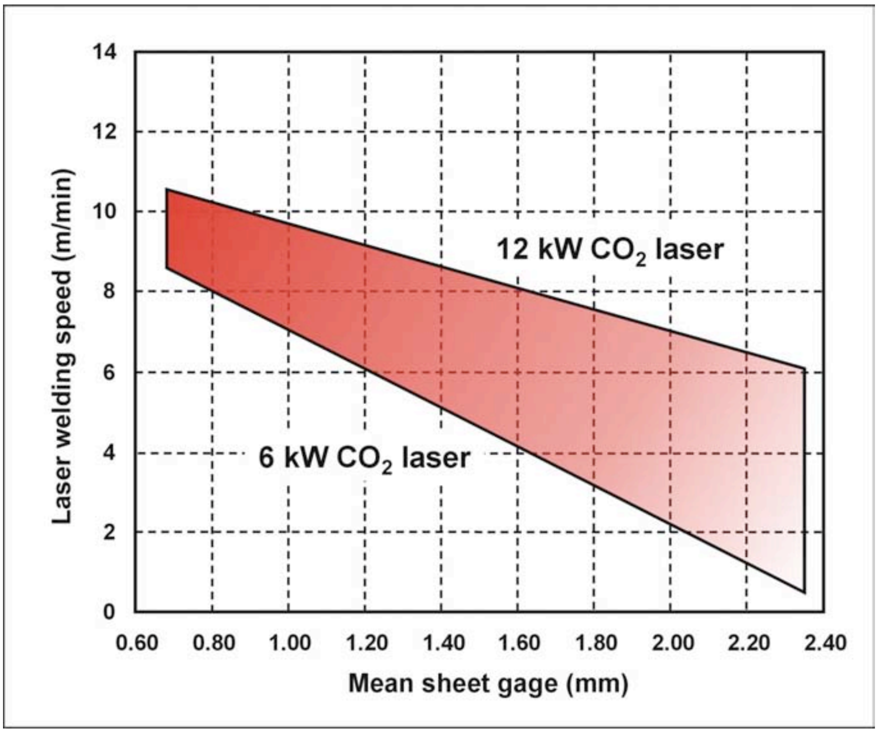

Fig. 1: Range of welding speeds depending on laser power and mean value of sheet gage.

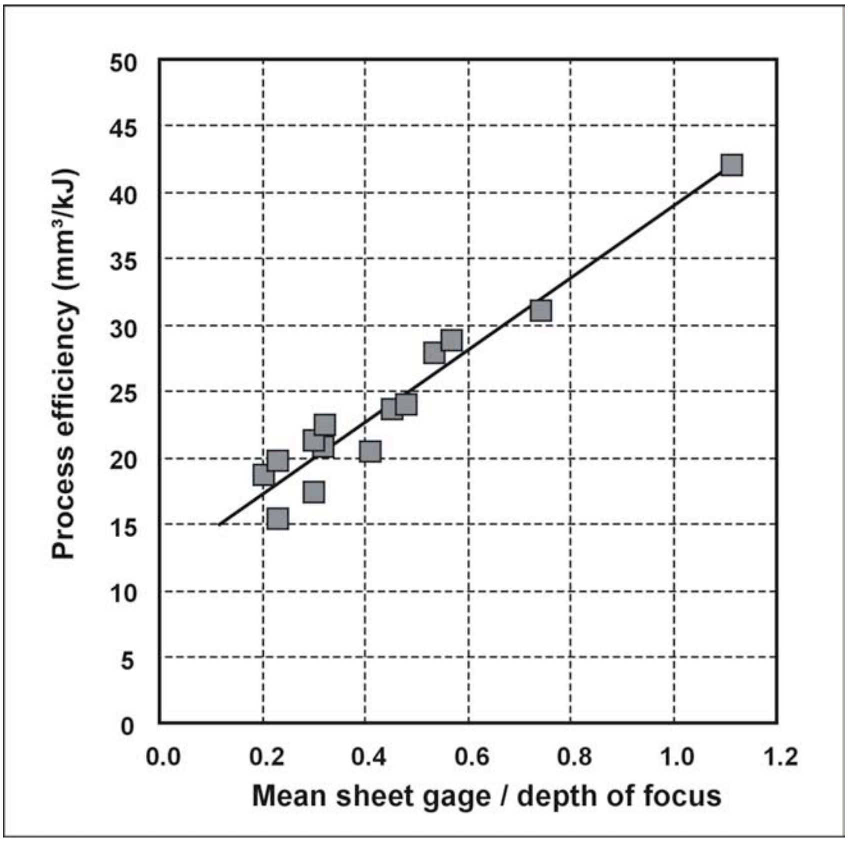

Fig. 2: Efficiency of laser energy conversion into molten metal for CO2 laser welding of thin steel sheet.

3.2 Dual focus welding

Gap related transmission is the result of an insufficient preparation of the sheet edges to be joined. The generally accepted requirement for autogeneous laser butt-welding is a butt gap of less than 0.1 mm along the entire joining distance. Precision cutting dies and stress free coil material are necessary prerequisites to achieve this strict requirement. The two characteristics of a suitable welding edge are a perfect straight-line accuracy as well as a high shear-to-break ratio. Attempts to compensate inferior edge quality resulting from conventional cutting dies by applying lateral pressure during welding did not prove to be a viable solution. A method that makes the laser butt-welding process more robust against small residual joining gap is the dual focus technique. Here, two partial laser raw beams are focused with a small defined separation to positions left and right of the joining gap so that the transmissive loss of laser radiation becomes negligible (Fig. 3).

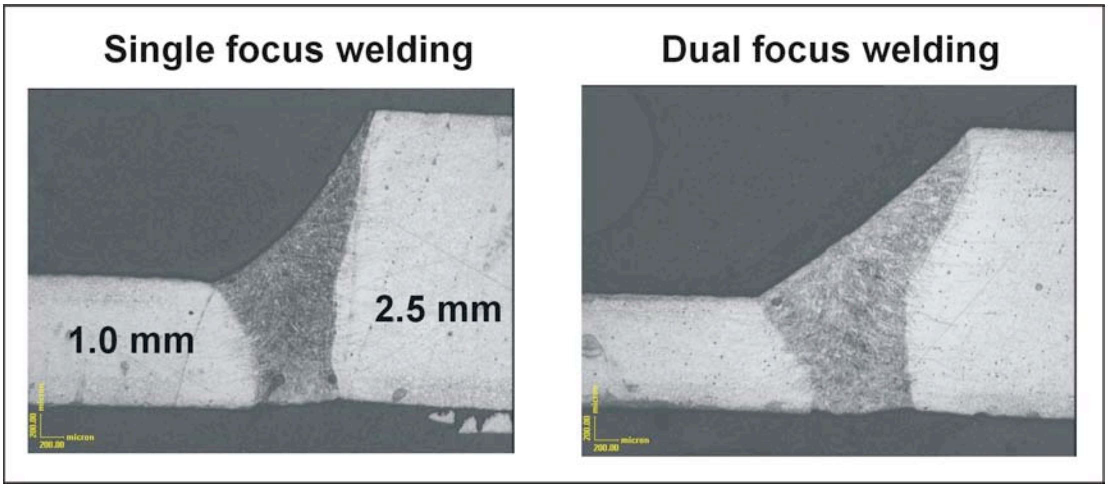

Fig. 3: Effect of beam focusing optics on weld seam cross section in CO_2 laser welding

3.3 YAG laser welding

Due to recent progress by laser manufacturers, YAG laser welding is gaining more interest for tailored blank production. The power of YAG lasers is still inferior as compared to CO2 lasers. However, YAG laser radiation has a wavelength that is 10 times shorter than that of CO2 lasers and therefore shows a higher absorption on steel. Furthermore, the YAG laser wavelength is not affected by plasma shielding. As a consequence YAG lasers allow a competitive welding speed despite of their lower beam power. The biggest handicap of traditional YAG lasers in the past has been the high investment cost and even more the higher maintenance cost. The latter applies to the excitation by flash light lamps. These have a limited lifetime of around 1000 hours. However, in typical blank welding applications the lifetime was found to be even shorter causing unpredictable layoffs and considerable cost. More recently flash light excitation is being replaced by diode pumping. The diodes are claimed to have a life time of more than 10.000 hours and provide also a better overall efficiency. Due to the latter, the thermal lens effect in the resonator is reduced resulting in a higher beam quality. Another advantage of YAG laser radiation is the possibility to deliver the laser beam by an optical fibre from the source to the workpiece.

4 Laser welding production concepts

For laser welded blank production various manufacturing concepts are used in the industry. These are the result of different production strategies and also of rapid parallel development of technology by different players in the market. A production concept is basically characterised by the way of achieving a relative displacement of laser beam and sheet material as well as by the manner of managing the material flow through the process. The driving forces behind any welding machine concepts are maximisation of the utilisation of the laser welding equipment, the optimisation of production flexibility and the reduction of cost.

4.1 Laser welding machine concepts

Fixed optics laser welding systems are characterised by a stationary welding head while the sheet assembly to be welded is passing underneath. This procedure allows producing straight weld seams of various lengths. Moving optics systems represent the opposite approach where the sheets to be welded are at rest while the laser welding head is executing the desired 2-dimensional trajectory. In this way weld seams of nearly arbitrary shape can be made. Numerous variations of these two fundamental machine concepts have been realised as well. The choice of the welding machine concept largely influences the way of positioning and clamping the sheets to be welded. Moving optics systems generally require a fixture tool also called "jig". The jig is often specially made for a particular blank configuration and, thus, represents a part specific investment cost. Another disadvantage of these systems is the more complicated beam delivery requiring multiple mirrors and special devices such as a beam telescope to compensate beam variation over the work envelope. Each mirror within the optical part contributes to the cumulative loss of available laser power at the working point. Here the YAG laser due to the beam delivery by an optical fibre brings a major progress. Since the length of the fibre is constant, beam properties remain the same at each point within the work envelope.

For the production of single straight welded assemblies, machines equipped with fixed optics are clearly the method of choice. Each additional straight weld in a blank design requires a corresponding additional pass through a fixed optics welding machine since only one weld seam can be manufactured at the time. This results in extra handling and machine set-up whereas a moving optics system finishes even complex multi-weld assemblies within one machine cycle. Therefore, a detailed analysis of the manufacturing cycle time is required to decide which of the two machine concepts is to be preferred. The duration of the welding cycle is composed of beam-on time determined by the boundary conditions such as available laser power and sheet gages and beam-off time due to leaping in between weld seams at accelerated speed.

The challenge to the material handling concept is to offer a new batch of unwelded sheets to the weld process as soon as the welding cycle on the previous is finished. This scenario allows a maximum productivity of the capital intensive welding equipment and thus leads to minimisation of the welding cost. The ideal solution in case of a fixed optics welding machine is a continuous material flow through the welding machine. In this case the welding speed represents the speed of conveying material into and out of the welding machine. Consecutive sheet batches are separated by a minimum intersection to keep the beam-off time as short as possible. In particular cases, the blank layout may induce an extended intersection between consecutive weld seams due to geometrical constraints of the blank contour. In this case an accelerated material flow in between weld sections helps to reduce the beam-off time.

Since welding cycles can be as short as a few seconds, appropriate buffer zones have to be foreseen at the beginning and the end of the continuous conveying system.

Fig. 4: Moving optics CO_2 laser welding machine with welding double shuttle jig system

4.2 Material handling concepts

Continuous material flow systems do not allow static clamping of the sheet pair during welding. However, the dynamic clamping that has to be used does not reach as high holding forces as a static system giving a risk of increased gap opening due to heat distortion especially towards the end of longer weld seams. As a compromise discontinuous feed systems have become popular where a shuttle takes a batch of subblanks and clamps them statically. Then the shuttle is passed through the welding machine. After unloading the welded blanks at the end of the welding pass, the shuttle is returning empty to the loading position. The return and refill periods define an additional unavoidable beam-off time so that the overall productivity is inferior to that of a continuous feed system.

Moving optics welding machines are also based on discontinuous feed systems. The part specific fixture tool is loaded with the blank set by robot. Final positioning of the different subblanks is done by actuators integrated in the jig. The handling cycle covering the blank loading and positioning before welding as well as the unloading of the welded blank represents a significant beam-off time. For this reason most machine concepts utilise a double fixture device to allow handling operation on one jig while the other is in the welding cycle. The two jigs can be mounted on a turn table revolving by 180 degrees or are attached on two shuttles moving in and out the welding booth individually (Fig. 4). It is still necessary to keep the welding cycletime larger than the handling cycletime. This can be achieved by grouping several blank sets into one jig driving up the welding cycle. Attempts to implement a continuous material flow in moving optics systems have not achieved yet a breakthrough due to considerable technical difficulties and the high investment cost for multiple jigs.

5 Future perspectives

Laser welded blanks have become an accepted product in modern automotive body construction. Straight line welded blanks with 1 or 2 weld seams for door inner (Fig. 5) and beams (Fig. 6) are currently among the most applications for laser welded blanks. More recently new challenges are emerging for the years to come [2]. First of all a trend towards more difficult blank designs is clearly observed. Thereby the degree of part integration becomes higher and material combinations become more extreme due to extensive use of high strength steel. An application gaining much interest is the body side frame, one of the largest parts in the automotive body. Laser welded blanks in this particular application allow to save raw material and thus costs but also result in considerable weight reduction possibilities (Fig. 7). The benefits on the manufacturing side are evident as well. Instead of stamping several individual sub-components that are spot welded together after forming, the laser welded blank results immediately in the final component after stamping. In this way press and assembly line occupation are much reduced as well as in plant logistics are simplified. The final part quality at the same time improves concerning tolerances and functional properties. Several leading players in the market began to make use of non-linear welded blanks in recent car models as well (Fig. 8). The driving force in this case is mainly the additional weight saving potential as reinforced areas in a base blank are being limited to the absolute minimum. Under these boundary conditions, moving optics welding machines will extend their share in the market.

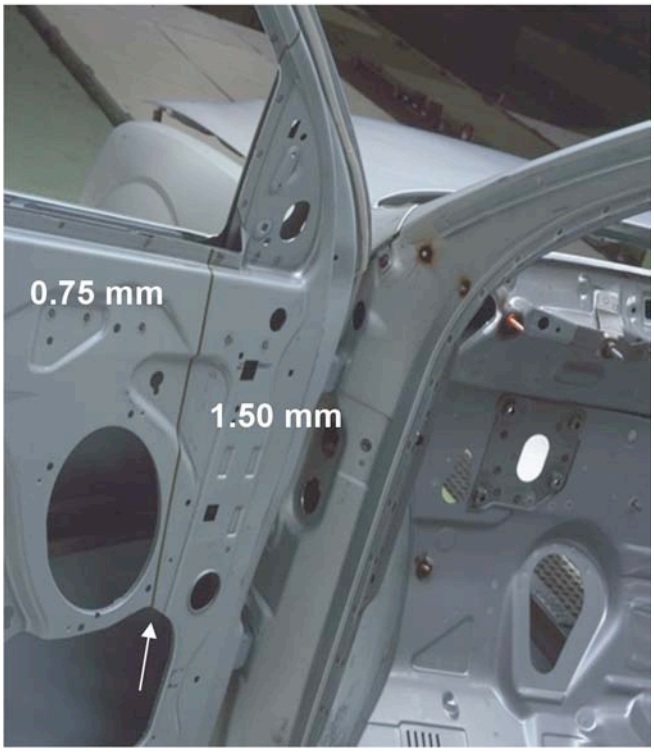

Fig. 5: Ford Mondeo front door inner with single straight weld

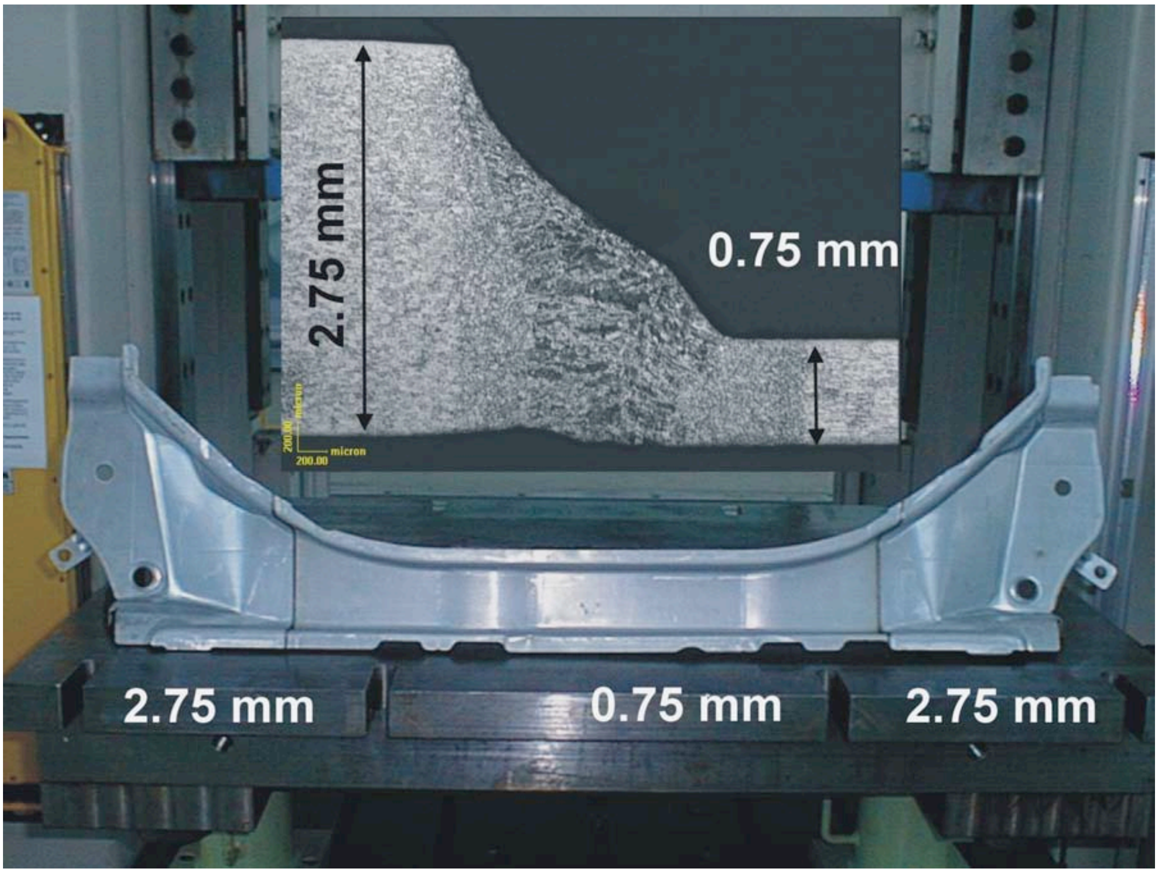

Fig. 6: Mercedes S-class cross member with extreme gage ratio

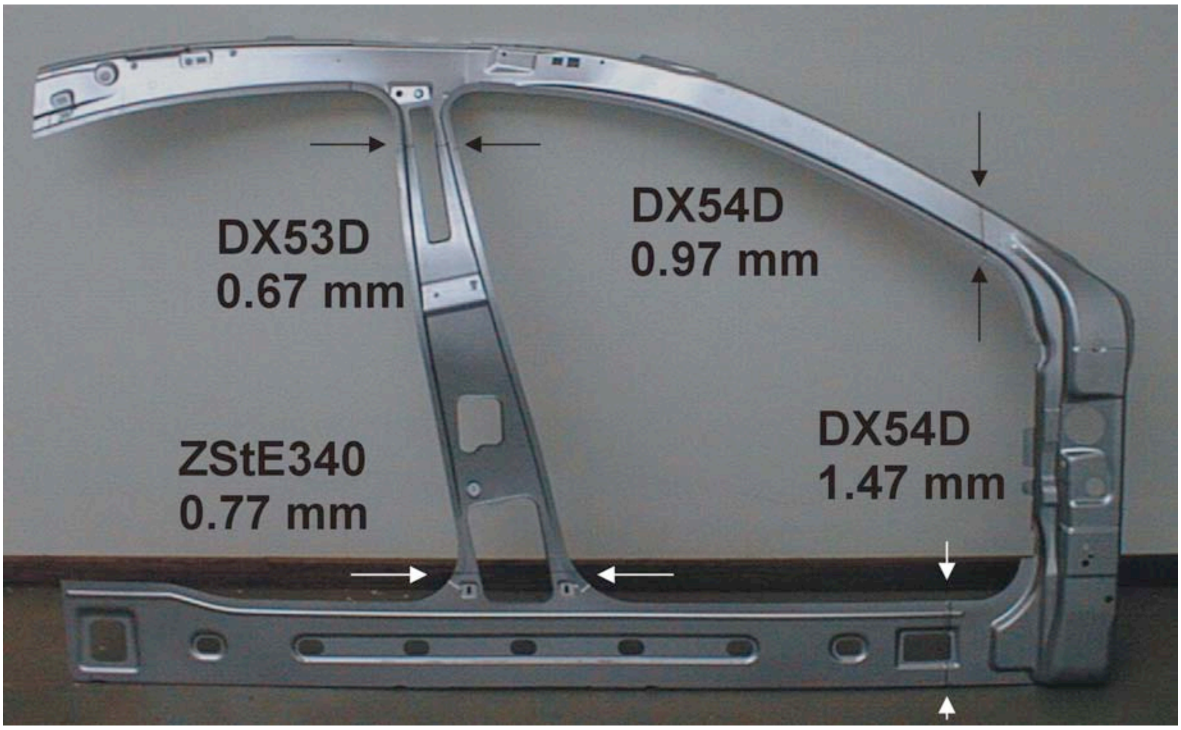

Fig. 7: 4-piece laser welded body side frame of the Peugeot 607

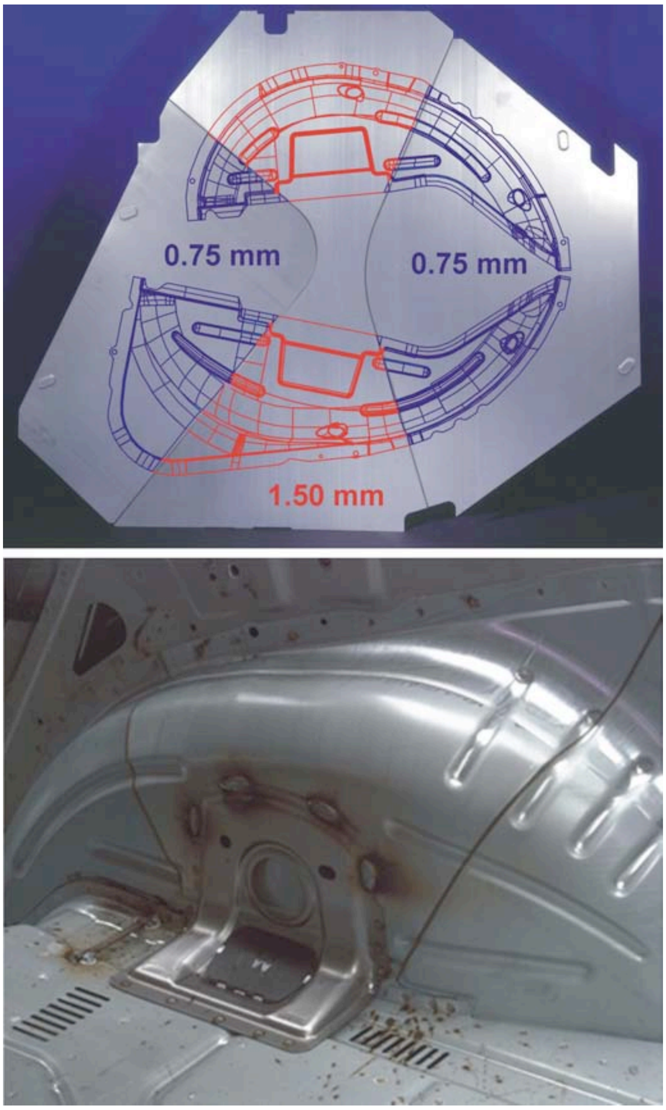

Fig. 8: Non-linear welded wheelhouse panel of the Ford Mondeo Wagon

The remaining mass market of laser welded blanks containing one to three straight weld seams is under high cost pressure due to the competitive situation amongst the suppliers and the stringent cost targets of the OEMs. This situation can only be faced by increasing the productivity of welding machines and by reducing machine investment cost. In that sense fixed optics machines fed by continuous material flow seem to be the most appropriate approach. Due to the efficient handling, the welding speed can be driven up with a direct impact on the productivity. The upper limit of the weld speed is set by the available laser power as well as by physical constraints of the laser keyhole welding process. Electron beam welding seems to have potential to surpass the existing laser weld speed limits. The combination of laser welding with other methods like induction or arc welding has also a positive effect on the speed but unfortunately deteriorates the mechanical properties of the welded blank due to an extended heat affected zone. Furthermore, additional process parameters are added using this hybride technique increasing its complexity significantly.