“All about Press Hardening”

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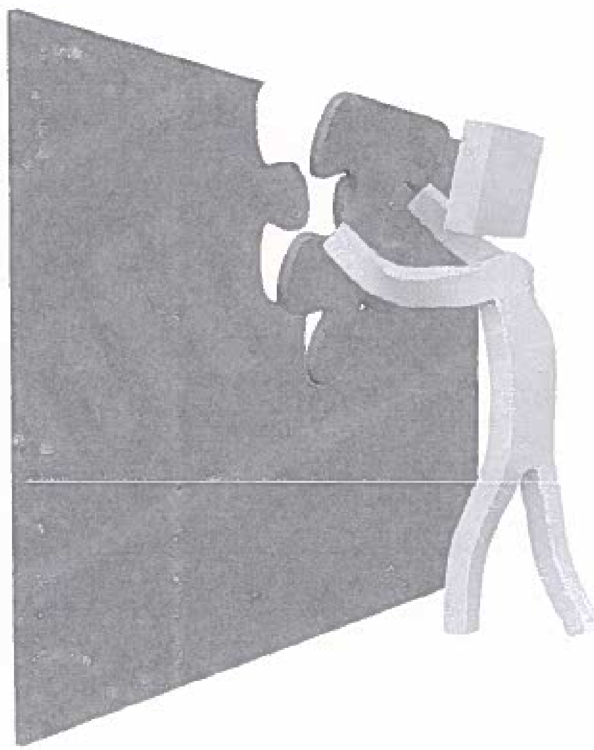
An Overview on Technology and Markets



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Preface

Actually, we are facing the biggest change in paradigm in metal forming technology since more than half a century. The source of this change is constituted by the worldwide trend towards an intense application of hot stamped / press hardened ultra-high strength steel components in modern body-in-white automotive structures, finally leading to superior crash performance and significant weight reduction.

Today hot stamping is undoubtedly a sustainable global technology. The expected surge in growth of this technology in part production, material supply, production equipment etc. has also given rise to some sort of unhealthy competition. Besides the well-known pioneers of this technology, who were amazingly often from SME-companies, many new players have appeared on the scene. Competition has risen inexorably and to be able to act globally has certainly become an existential challenge.

It has however been clearly understood during these years that press hardening is an inevitably knowledge-driven technology. Without a proper understanding of the governing thermo-mechanical mechanisms it is perhaps possible to move along the "low-end" of technology but impossible to reach the "high-end". Therefore, there are still very promising opportunities also for SME-companies in reaching and/or maintaining their position at the "high-end" of hot stamping technology and to share/benefit from the high level of added value. The acquisition of substantial knowledge, therefore, constitutes the main "key" to be successful in the aforementioned sense.

To achieve this, being part of a network and having access to information on technological developments in the same way as to economical market data and facts becomes a key-factor when it comes to meet competition and, finally, to belong to the successful global players in technology.

Kassel, Germany

Prof. Dr. Kurt Steinhoff

Contents

1 Introduction

The ubiquitous discussion of environmental aspects as for instance preservation of natural resources and climate changes represents only a part of a holistic approach towards safety. Energy safety and climate safety are in the same way components of this interdependent system as the aspect of individual and economic safety [1], **Figure 1**. To improve or at least to maintain safety in the aforementioned holistic sense, several multi-national agreements and pursuant legal regulations on international and national level have already been established and are under continuous further development [1].

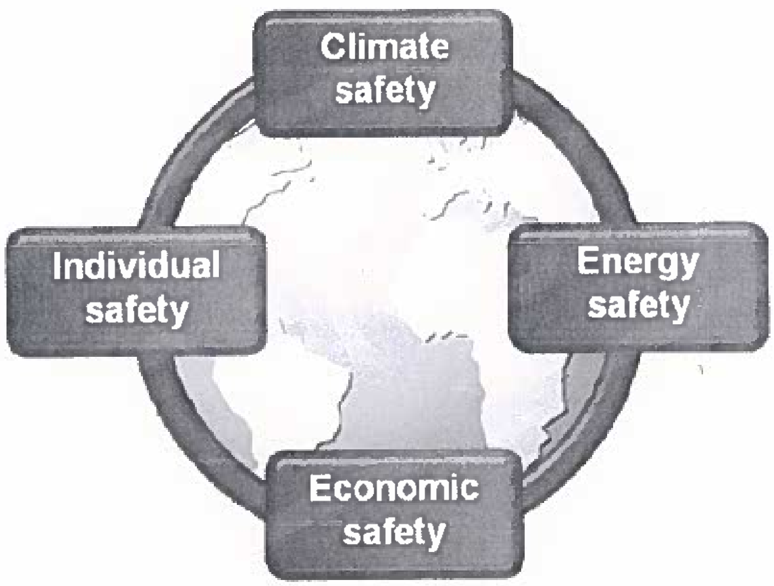

Figure 1: *Dimensions of safety in the context of global changes and threats (source: Germanwatch e.V.)*

Since mobility constitutes one of the major impacts on safety in the previously mentioned sense, it is comprehensible that energy consumption and CO_2-emission as well as passenger safety are primary targets of these regulations directly addressing individual, energy and climate safety. Projecting these targets to the design of a typical passenger car, the availability of highly innovative technical solutions, which are comprehensively able to meet these diverse safety requirements, becomes essential. Since the body structure constitutes the biggest share within the weight balance of a typical passenger car [2], **Figure 2**, body-in-white design principles and the choice of engineering materials are key issues of being competitive and, quasi as a feedback loop, by this affecting economic safety as well.

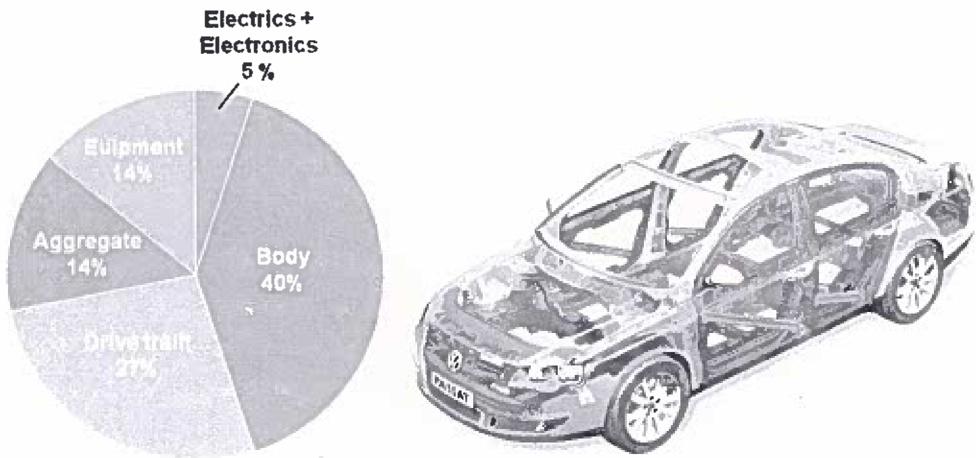

Figure 2: *Contribution of different subsystems to the total weight of a passenger car (source: Volkswagen AG)*

In this technological context, new types of thermo-mechanically coupled process routes in sheet metal forming appeared on the technological scene. With these technologies, better known as *press hardening* or *hot stamping*, parts with highest geometrical complexity and, at the same time, ultra high strength can be produced. Unfortunately, ductility and, therefore, the ability to transform impact energy into a controlled plastic deformation of the car body structure are limited. Coming from that, the ongoing trend towards further system consolidation with a significantly higher functional integration on single component level has encouraged the development of several approaches to exceed these limits. Among these approaches, strategies to produce parts with tailored properties constitute doubtlessly the most prominent example. Other important issues are shortening of process chains, robustness of processes, extension of substrate material range, improvement of corrosion resistance and new fields of application.

2 Technological Background – *„How it all started“*

In the early 1980'ies it became obvious that available cold deformable steel has reached its limits when it comes to contribute to the improvement of crash performance and reduction of weight for passenger cars by an ultra-high level of ultimate tensile strength, **Figure 3**.

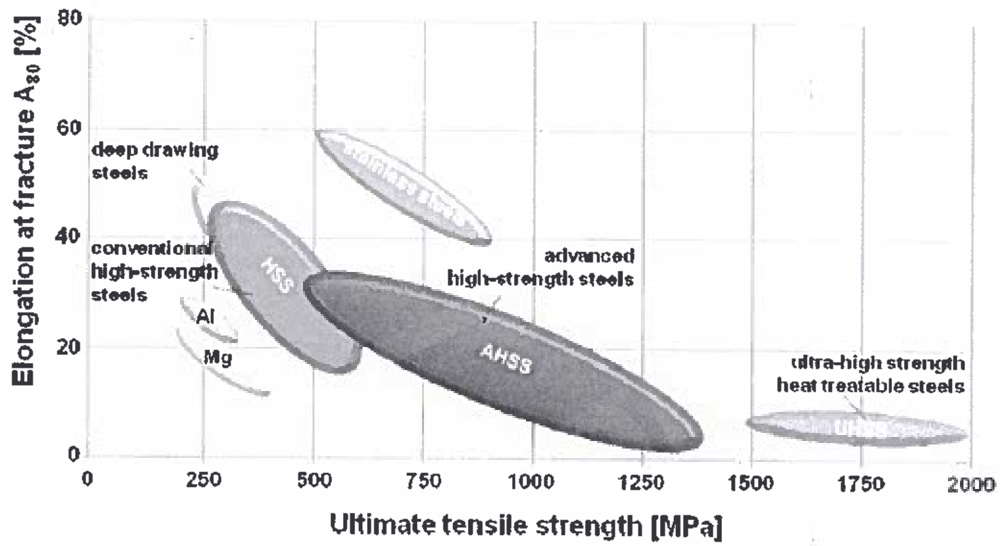

***Figure 3**: Property range of commercially available steel grades; limited strength and/or ductility for cold deformable steels; unexploited potential of ultra-high strength heat treatable steels*

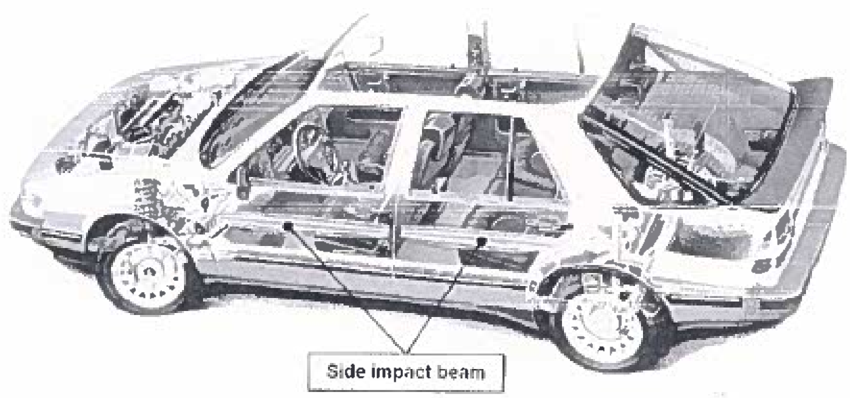

***Figure 4:** Side impact beam in Saab 9000; first automotive series application of press hardened components (source: Saab Automobile SA)*

To overcome this technological restriction, ultra-high strength heat treatable steel was applied in combination with a new type of hybrid thermo-mechanical manufacturing technology. Consequent research and development including upscaling of results to an industrial serial production level, led already in 1986 to the first successful introduction of a new generation of side and front crash reinforcement components in the Saab 9000 [3, 4], **Figure 4**. This thermo-mechanical sheet forming technology which was sustainably able to gain access to the production of ultra-high strength steel (UHSS) parts was and still is called *press hardening* or *hot stamping*.

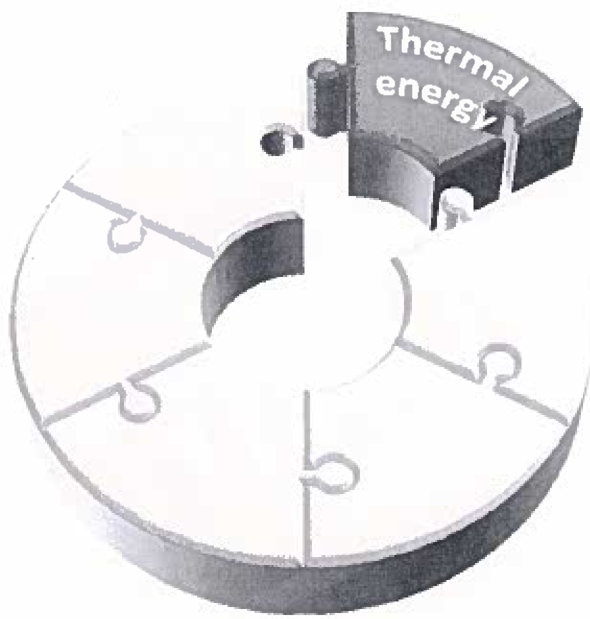

***Figure 5**: Thermal energy – the missing link towards exploitation of ultra-high strength steel for body-in-white application*

The simple underlying idea of this approach is to introduce heat, **Figure 5**, into to a sheet forming process to improve formability by deformation within the austenite state and to promote transformation hardening by controlled closed-die cooling, **Figure 6**. Therefore, press hardening or hot stamping constitutes nothing else than a combination between hot forming and heat treatment, **Figure 7**.

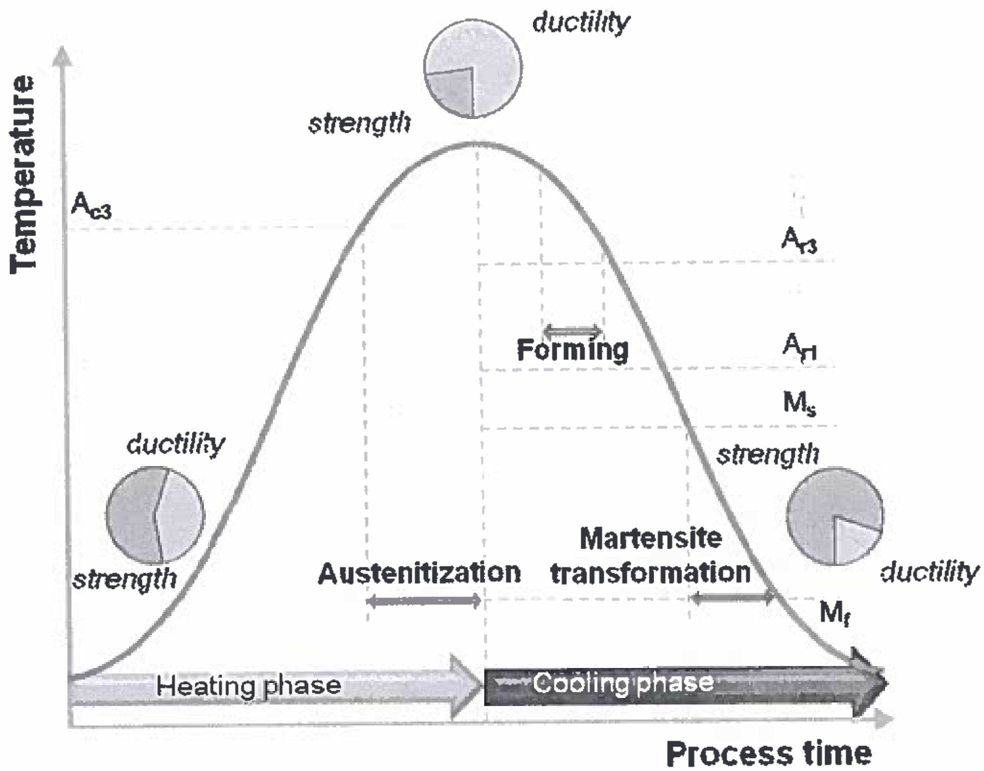

***Figure 6**: Schematic time-temperature course of a press hardening process; heat-induced increase of formability, forming in the austenite state, adjustment of ultra-high strength by process integrated transformation hardening*

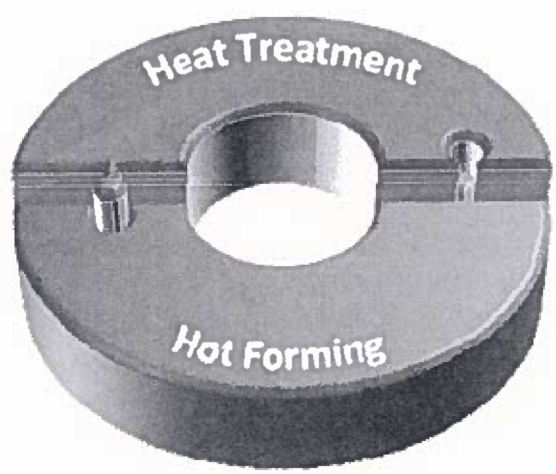

***Figure 7**: Press hardening / Hot stamping – integrated thermo-mechanical processing consisting of a combination between heat treatment and hot forming*

From that time, especially press hardened door impact beams and front bumpers became state-of-art in body-in-white application [4-6].

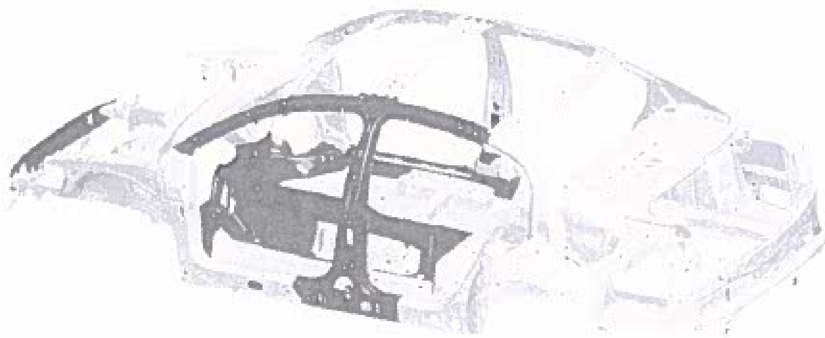

Figure 8: *6th generation Volkswagen Passat; integral ultra-high strength steel (UHSS) design of the passenger compartment (source: Volkswagen AG)*

A real change in paradigm started in 2004, when Volkswagen AG in Germany decided to apply an integrated passenger compartment mainly consisting of press-hardened components for their newly designed 6th generation of the Passat model, **Figure 8**. Not only the design principle itself was completely new at that time but also the complex shape of the individual components applied, **Figure 9**.

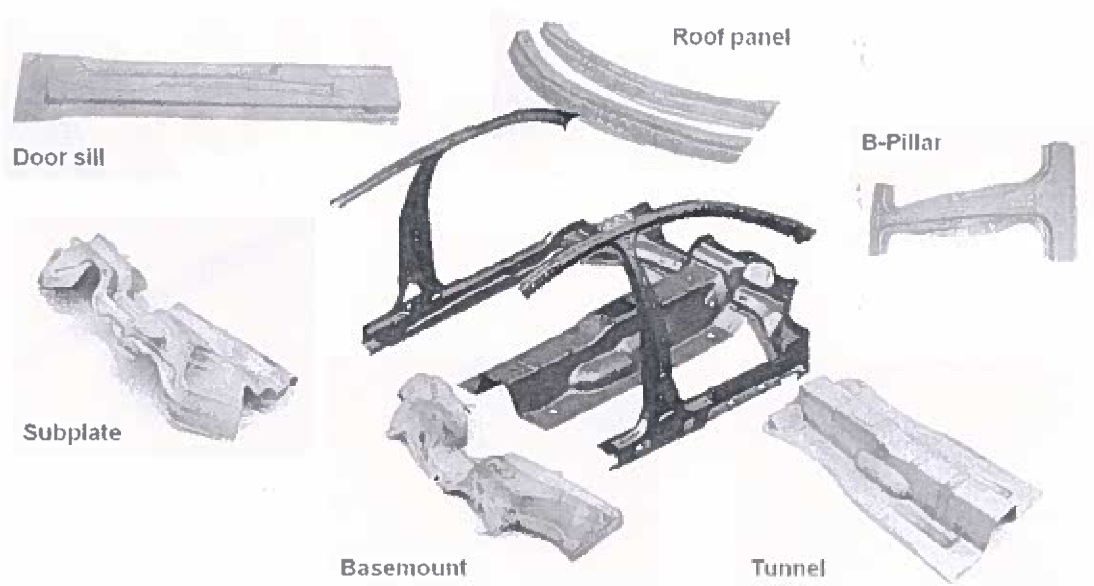

Figure 9: *Press hardened components (source: Volkswagen AG)*

The reason for this decision was mainly driven by the aim to avoid a further increase in weight. Although, new product features represent a theoretical increase of about 100 kg between the 5th and 6th generation, this could be practically compensated by a consequent lightweight design philosophy maintaining the total weight nearly constant, **Figure 10**.

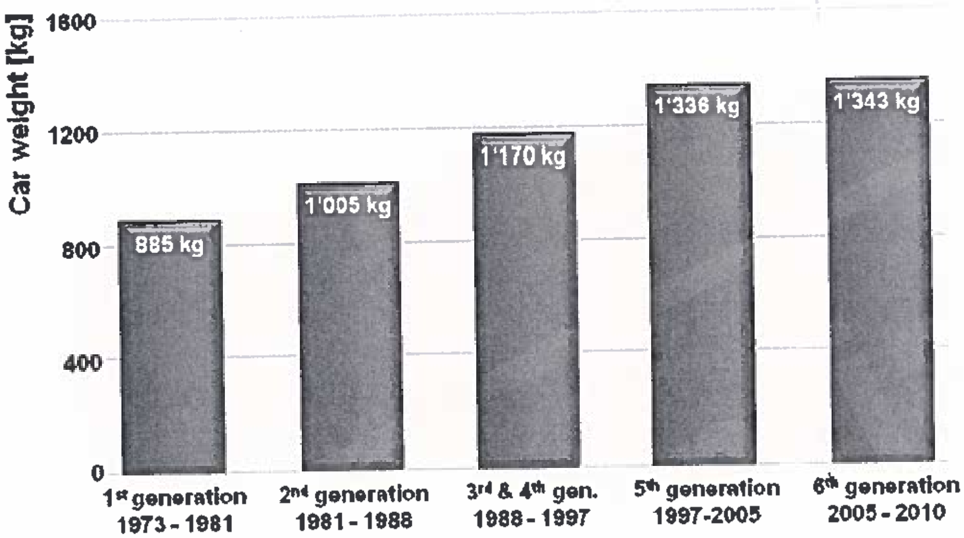

***Figure 10**: Weight development over different model generations of the Volkswagen Passat (source: Volkswagen AG)*

In this context, the consequent application of press hardened UHSS parts could contribute about 25% to this weight reduction by subsystem consolidation and smaller wall thickness of the components [5, 7]. **Figure 11** shows the design changes and resulting weight reduction between the 5th and 6th generation exemplary for the B-pillar and for the tunnel. However, press hardening is not just a "slimming diet" for the body-in-white structure with respect to its weight; the improved stiffness of the UHSS-design additionally leads to a significantly improved lightweight quality [2], **Figure 12**.

Regarding crash performance, the 6th generation of the Volkswagen Passat became a benchmark, due to its superior intrusion resistance, **Figure 13**. From this point, the number of press hardened UHSS parts grew continuously and, therefore, shifting press hardening from a niche technology into a globally applied mass technology in sheet metal forming [5].

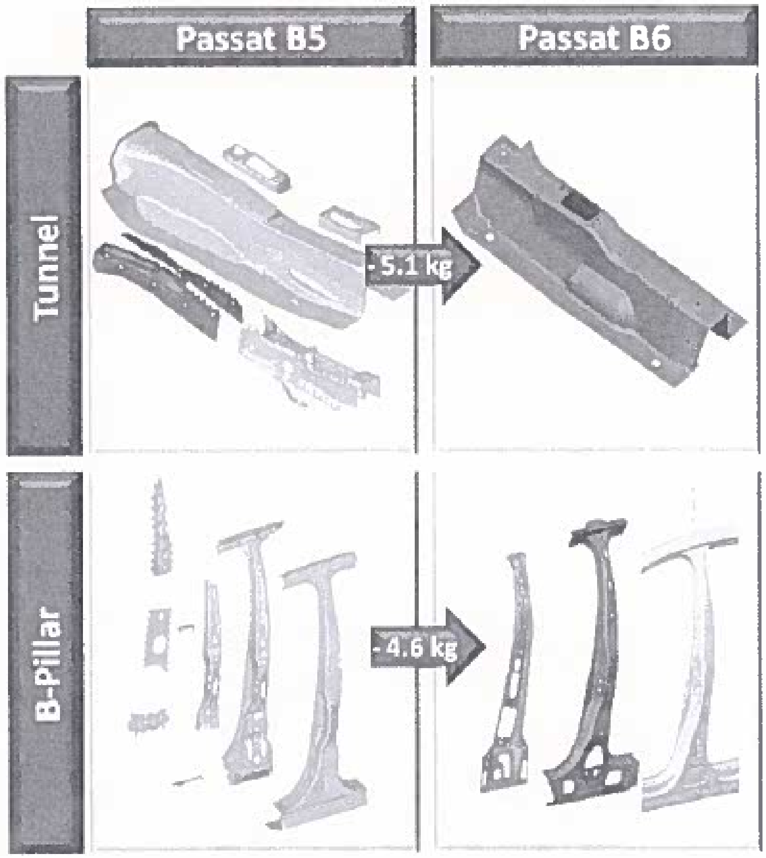

***Figure 11**: Part consolidation and weight reduction by application of press hardened parts (source: Volkswagen AG)*

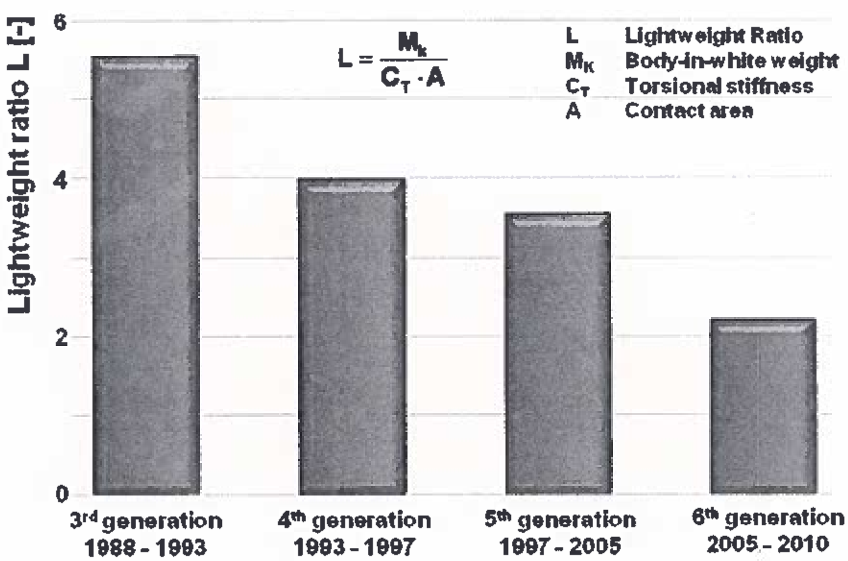

***Figure 12**: Development of Lightweight ratio over different model generations of the Volkswagen Passat (source: Volkswagen AG)*

Figure 13: *Crash performance of the Volkswagen Passat B6 (source: Volkswagen AG)*

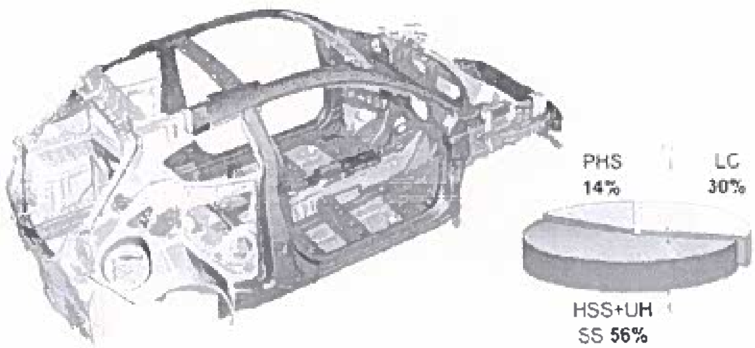

Figure 14: *UHSS body-in-white design for the compact car model Alfa Romeo MiTo (source: FIAT Group Automobiles S.p.A.)*

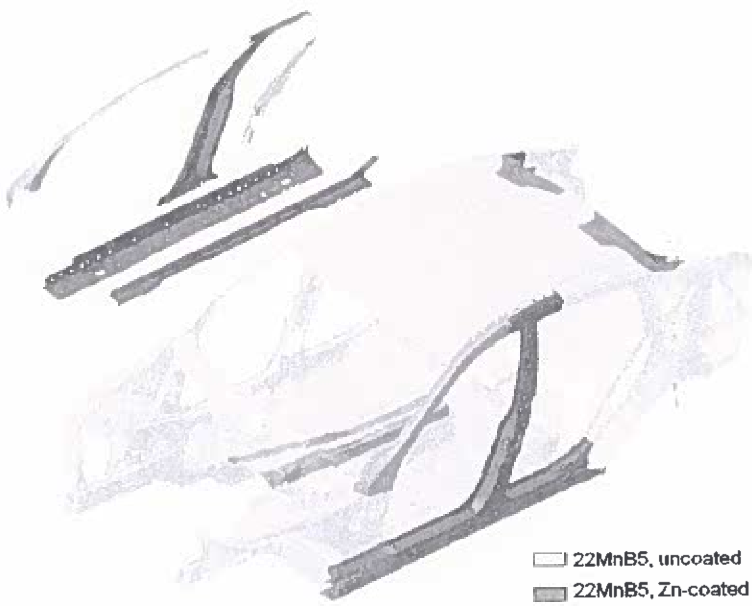

Figure 15: *UHSS body-in-white design for the mid-range car model BMW 5 series (source: BMW AG)*

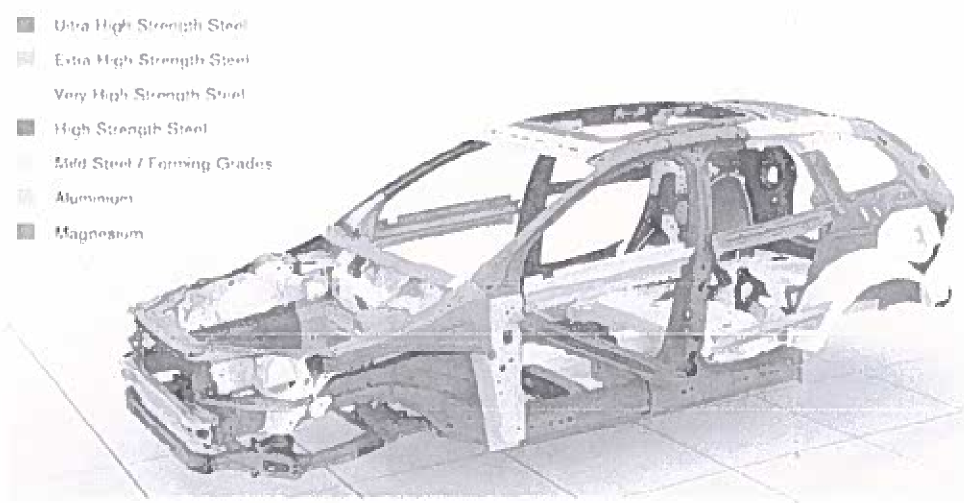

Figure 16: *UHSS body-in-white design for the SUV model Volvo XC60 (source: Volvo Car)*

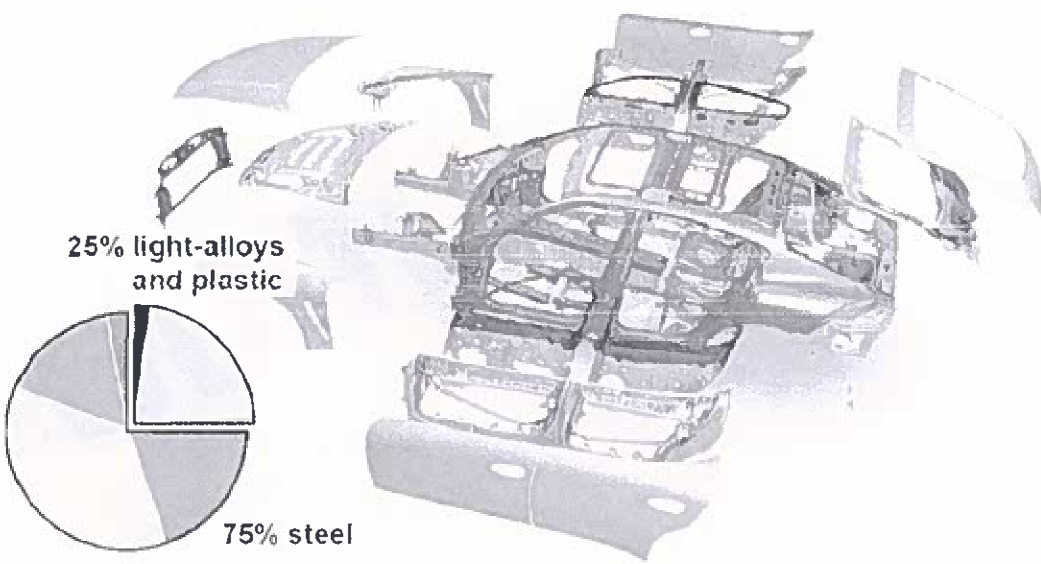

***Figure 17**: Multi-material design of the top-of-the-range car model Porsche Panamera (source: Dr- Ing. h.c. F. Porsche AG)*

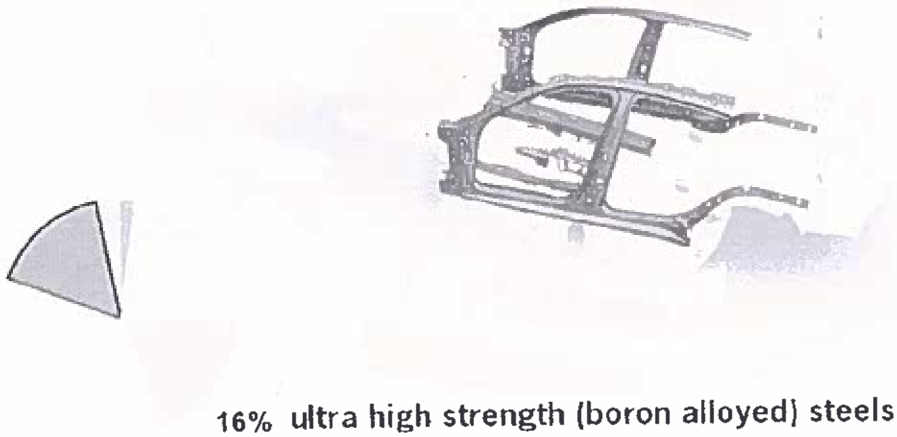

Figure 18: Fully integrated UHSS passenger compartment of the top-of-the-range car model Porsche Panamera (source: Dr.-Ing. h.c. F. Porsche AG)

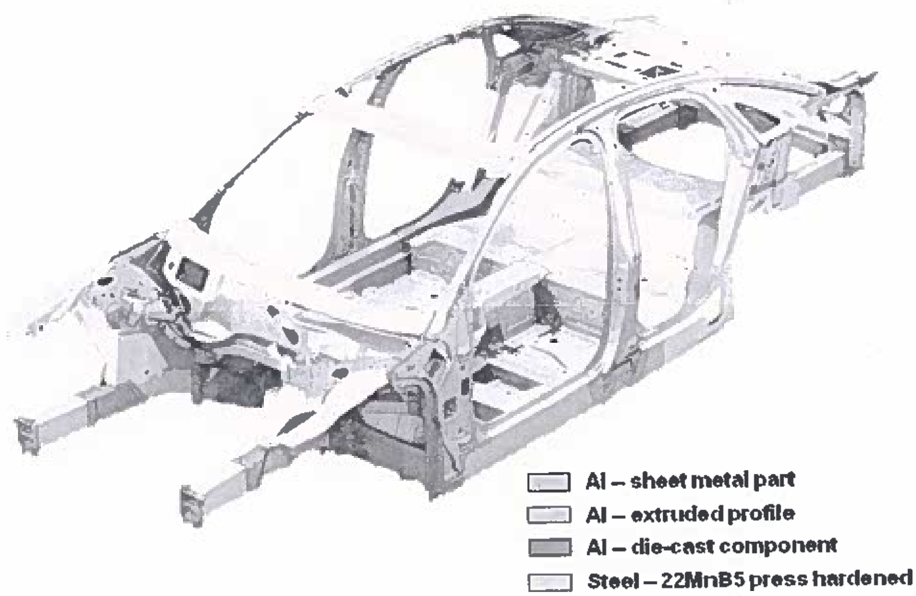

Figure 19: Aluminum body-in-white structure of the top-of-the-range car model Audi A8 – application of a press hardened steel B-pillar (source: AUDI AG)

3 State-of-the-art – *"Where we are today"*

3.1 Body-in-White Design

Currently there is nearly no body-in-white design for large-volume passenger car models without press hardened components. This counts as well for compact cars, **Figure 14**, as for mid-range cars, **Figure 15**, and for SUV's, **Figure 16**. **Figure 17** shows a multi-material design of the Porsche Panamera. Also this top-of-the-range model has a fully integrated UHSS-passenger compartment consisting of press hardened components, **Figure 18**. Generally, a consequent substitution towards press hardened parts within the highly crash-sensitive zones of the car body structure can be observed. Even from a puristic Aluminum body-in-white design perspective, the advantageous performance of press hardened steel apparently makes their application virtually unavoidable when it comes to parts with highest requirements on crash performance, **Figure 19.**

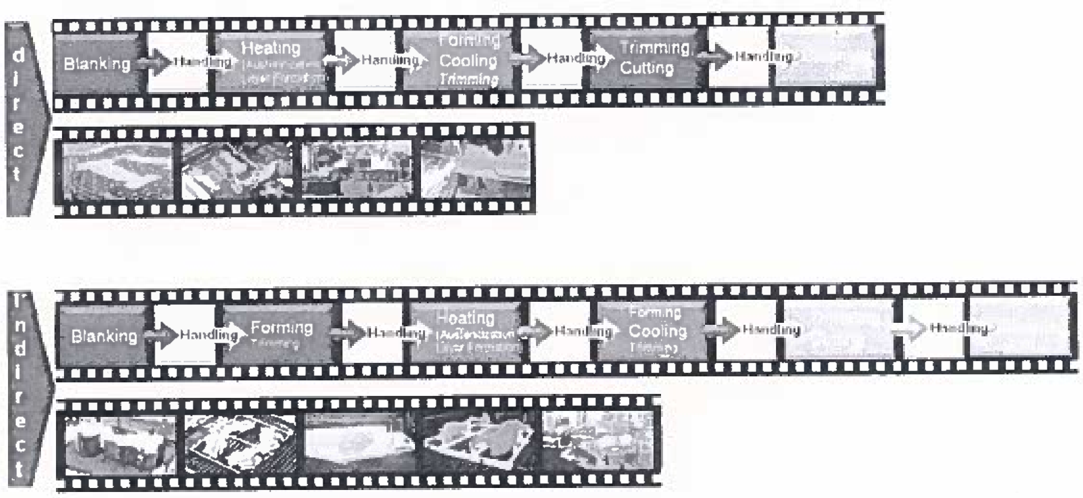

***Figure 20**: Process chains for direct and indirect press hardening (pictures: Volkswagen AG)*

3.2 Process Technology

Finally, press hardening constitutes a thermo-mechanically coupled manufacturing process, in which forming is performed in the austenite region, in order to utilize the low flow stresses, high formability and the residual stress free state of the material. Complex shapes with negligible spring back can be achieved in only one forming step. By rapid cooling under closed die contact, a phase transformation from austenite to martensite deploys highest resulting ultimate tensile strength in the final part [5].

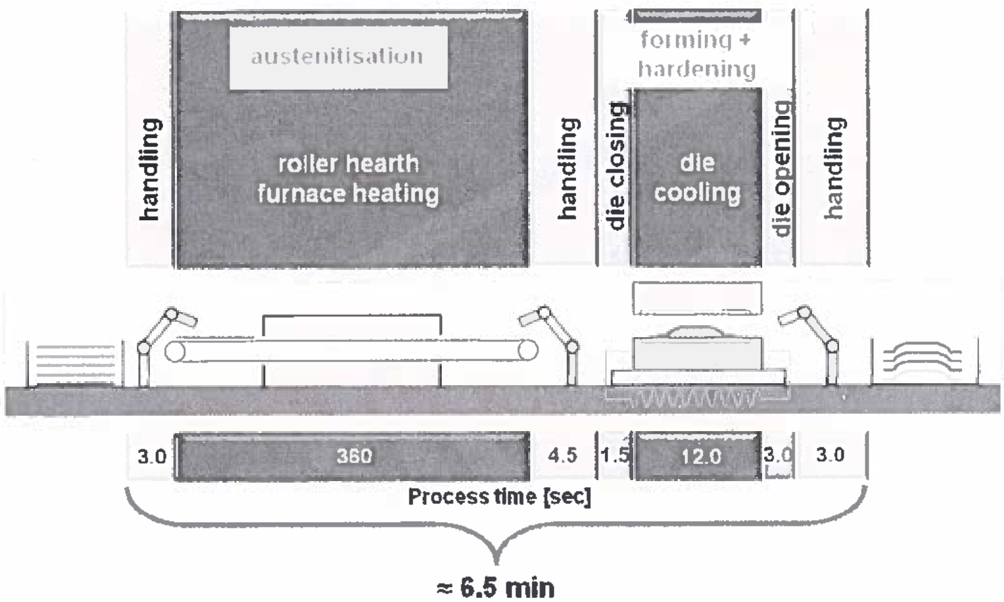

***Figure 21**: Exemplary process cycle for direct press hardening of an AlSi-coated steel 22MnB5*

Two different types of processes are known: so-called *direct* and *indirect* press hardening, **Figure 20**. The difference between these process routes is constituted by a partial or complete cold pre-forming before heating, hot forming and cooling at indirect press hardening. **Figure 21** shows an exemplary process cycle for direct press hardening of an AlSi-coated steel 22MnB5. **Figure 22** shows the corresponding time-temperature profile of the workpiece.

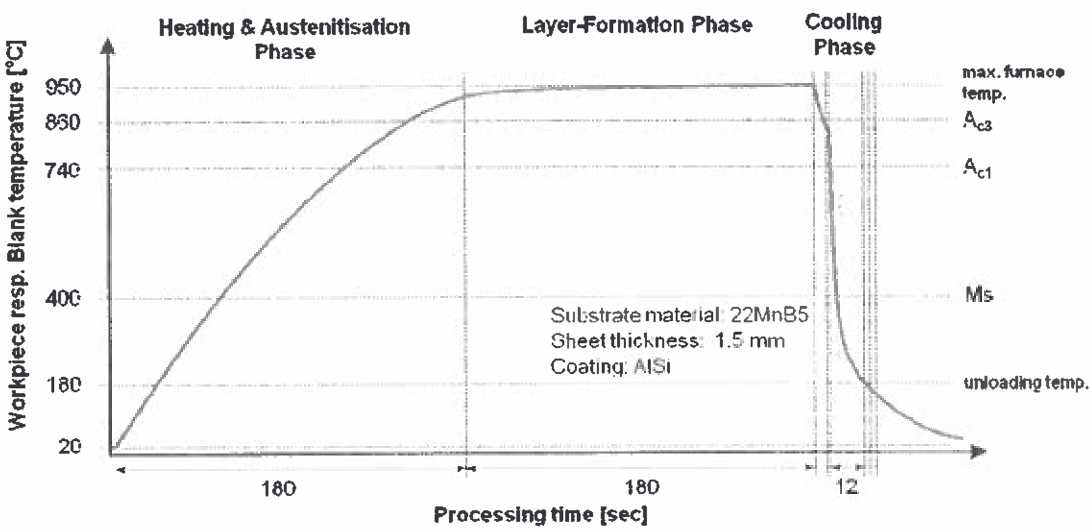

***Figure 22**: Exemplary time-temperature profile of the work piece for press hardening of an AlSi-coated steel 22MnB5*

After press hardening the parts are cut [8, 9] and coated with organic coatings. Additionally, shot blasting or pressurized gas cleaning can be necessary to remove remaining oxides from the surface. Also tempering can be applied to adjust the strength/ductility ratio.

3.3 Materials and Coatings

Among the typically applied heat treatable steel substrates, heat treatable steel 22MnB5 is most widely used for press hardening. The metallurgical composition, especially Boron and Manganese as alloying elements, aim at a sufficiently large period of process time for Martensite formation [10-12].

In this context, it has to be taken into account that this time period is not only influenced by the chemical composition itself but also by the governing mechanical stresses during coupled forming and cooling [13].

Although material ductility regarding its formability in hot state is superior compared to any cold forming, the ductility of the final part with respect to its crash performance actually still leaves some room for improvement. This room, of course, can be filled by the choice of new types of steel grades. Investigations on hot sheet metal processing of different steel grades can be found in [14].

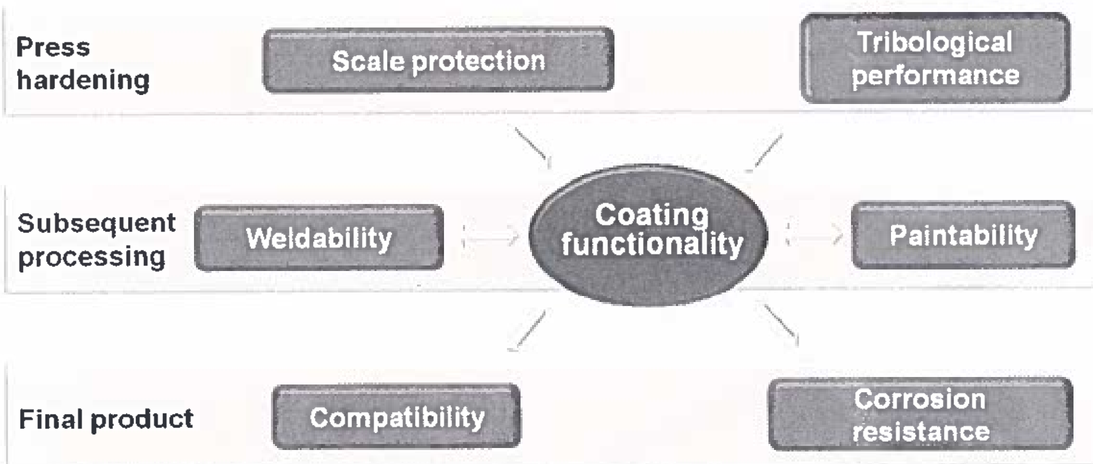

***Figure 23**: Multiple functional requirements on coatings for application in press hardening*

Due to the high process temperatures, **Figure 22**, uncoated material leads unavoidably to severe oxidation resulting in an undesirable formation of scale, which has to be removed not only from the part surface but also from all parts of the process equipment. To avoid this, different types of coated steel systems are applied [11, 19, 20]. The physical and chemical properties of these coatings regarding their applicability for press hardening but also regarding their behavior during subsequent processing of the press hardened parts and performance of the final product leads to a complex profile on required functionalities, **Figure 23**. **Figure 24** shows an overview of those systems, which are actually applied in series production.

Beyond the aforementioned hot-dip galvanized and hot-dip aluminized coatings, also electro-galvanized [21] and wet-chemical coatings are known [22, 23].

In most cases, these coatings themselves need a defined heat induced formation, **Figure 18**, to maintain their integrity and, therefore, being stabilized by a controlled surface passivation and/or controlled diffusion between coating and substrate [11, 19, 20]. What should be avoided in any case is the formation of melt on the surface during heating and hot forming, which leads to pollution and subsequent damage of the transport devices in the furnace [24] and of the tool surface by melt adhesion. For the choice of tool materials and coatings, the characteristic tribological behavior of the different type of coatings and its dependency on the heating conditions have to be taken into account [25-29], **Figure 25, 26**. The choice of the time-temperature course during heating also affects weldability and paintability of the press hardened part.

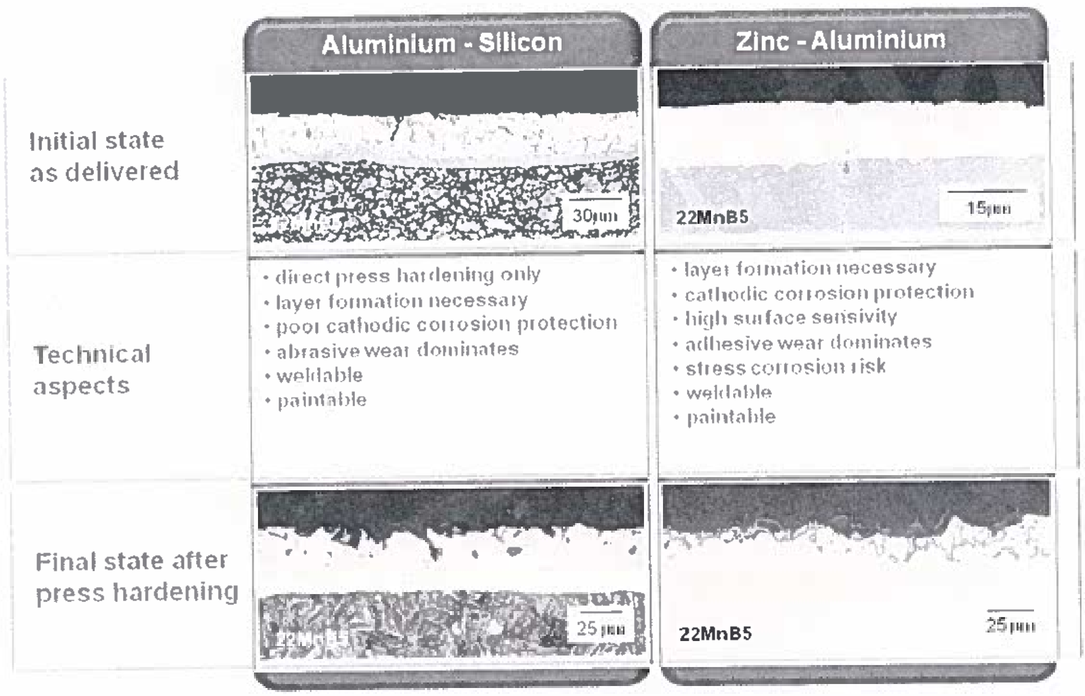

Figure 24: *Coating systems applied for industrial hot stamping; hot-dip galvanized (right) and aluminized (left) coatings before (upper part) and after (lower part) press hardening*

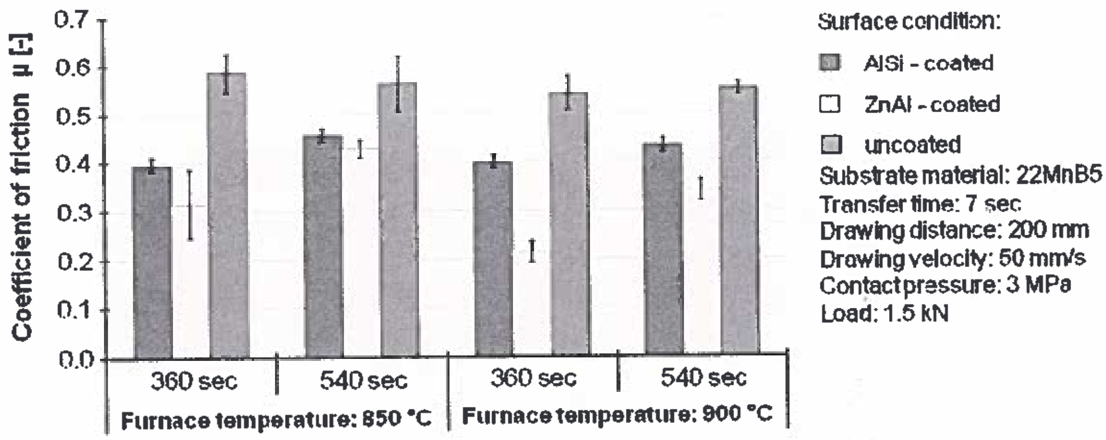

***Figure 25**: Influence of heating conditions on the tribological behaviour of different types of industrially applied sheet-surfaces during press hardening*

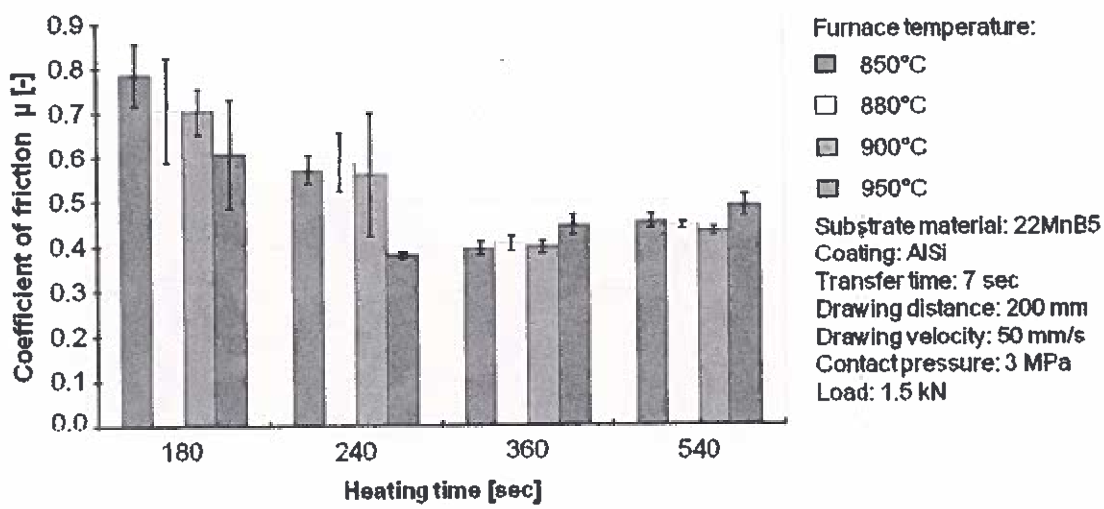

***Figure 26**: Influence of heating conditions on the tribological behaviour of hot-dip aluminized heat treatable steel*

4 Market Development – *"It's time for clever strategies"*

In the last few years a remarkable growth in press hardening of ultra high strength steels (UHSS) has been observed in the automotive industry [39-43]. During his opening speech at the 3rd International Conference on Hot Sheet Metal Forming of High Performance Steel - CHS² 2011, Hans Eichel, German Federal Minister of Finance retd., analyzed the chances and challenges in this rapidly growing market as follows:

"What I realized during the preparation of this speech is that innovation in hot sheet metal forming was mainly driven by only a few pioneers. Remarkably, among these pioneers, small and medium-sized enterprises took over a key-role. While, at that time, the big players in metal working technology obviously concentrated on their core markets and left the upcoming hot forming technology almost completely out of their focus, the pioneers went to new frontiers in technology and finally succeeded in offering new technological opportunities for product and process performance regarding efficiency and safety. By transferring these opportunities to a large volume automotive production scale, a real opening of the global market finally was initiated by first original equipment manufacturers only about 8 years ago. Expectably, others started to follow with a certain delay.

For this impressing movement, the main investments in knowledge and new products were carried by only a small core-group of highly specialized players. The continuous distinct growth over several years gave rise for prosperous business for these companies finally benefiting from their achieved key position during this period. However, in many cases a full return on investment could not been *reached before the financial and economical crisis started in 2008. Due to the unpredictable market development, the almost complete interruption of investment activities, the drastic drop of production quantities, the unavailability of financial resources and drastically reduced R&D activities in this period, these small and medium-sized enterprises just had to survive on existing contracts; their high level of specialization did not leave any other market option and, instead of the expected further growth, a severe drop in their target market. On the other side, new "global players" started to enter the previously underestimated and neglected hot forming technology and its markets simply driven by their efforts to survive by a compensation of the drop in their former core markets. At least since that time, there are an increasing number of companies, as well small and medium-sized as real big enterprises, being well prepared to share from and to compete for the rapidly recovering global market volume evolving since late 2009 and early 2010.*

However, none of them and nobody else expected the actual dimension of growth regarding spontaneous market acceleration and velocity. This highly dynamic evolution can be attributed to the fact that real market penetration of hot forming technology was almost completely hidden behind the dramatic drop in production quantities during the crisis while, at the same time, ultra-high-strength hot formed parts were extensively applied in almost every next generation body-in-white design.

The real challenge right now is to keep up-front in this ongoing global race. To keep up-front in this context means, of course, to succeed in building up global production capacities and professional logistic chains including the provision of maintenance and assembly resources in the same way as local part supply and local content. However, it also means to have access to financial resources for further investment, and, to handle the liquidity needs of a large number of parallel export contracts all over the world. Since hot forming finally is a knowledge driven technology, the availability of human resources and access to adequate *qualification and training becomes crucial.*

We should not forget that, additionally, the driving forces for further innovation have to be kept alive at the same time.

To handle all these streams of information and activities, properly and carefully coordinated procedures are essential. Market forecast, technological trend scouting and risk analysis constitute an indispensable source for the development of sustainable strategies.

Let me state this very clear: ***Your particular field of technology has reached a dimension where well-conceived and clever strategies are absolutely inevitable for being competitive.***

All this is already quite ambitious for the existing players. However, regarding the growth and the resulting chances hot forming cannot and will not remain a "closed shop" for a limited number already involved "customers". There is no doubt about the fact that these "already involved players" have valuable knowledge and skills to maintain their short-time-to-market access at their disposal. However, the growth itself and the still unexploited technological potential give rise for new players searching for new chances and, therefore, facing unexplored challenges.

Coming from that there is absolutely no doubt that the more complex your particular technological world becomes, the stronger becomes the need for comprehensive insight, networking and exchange."

In order to face the generally growing market demands, globalized logistic chains have been developed successfully during the last ten years with advantages like cost efficiency and fast ramp ups for full serial production. However, it has also become obvious that these globalized logistic chains are more sensitive to quick changes in required component properties and other market influencing factors [44, 45]. After some years with high rates of growth in the production of press hardened components, the financial crisis of 2008 unfortunately led to an inconstancy in output figures and, therefore, to an uncertainty in production planning and scheduling as well for the OEMs as for their component suppliers. However, at the same time, the substitution towards application of hot-formed UHSS within the body-in-white structures kept on going. Unavoidably, a lack of information for reliable prediction of future technological trends and market development in the particular field of press hardening evolved. All this finally reveals a strong need for a methodology based tool for market and technology monitoring and forecast, which also enables to take the complex interdependencies of the above-mentioned globalized logistic chains into account.

Primarily, this tool should serve as a valuable information source for monitoring and prediction of global and regional production capacities, technological trends, required infrastructure developments and innovation activities. At the end of the day, however, the availability of this tool should support important strategy decisions and help to reduce the risk of misperception and paucity of information.

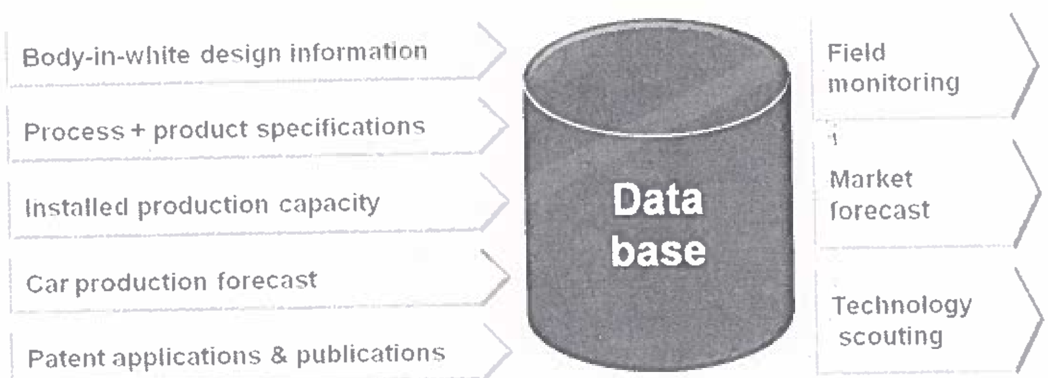

***Figure 27**: Data base structure: Incoming streams of information and extractable output*

Although several well-known market studies are available, their significance for the highly specialized press hardening market remains limited, since they mostly cover global car production rates [46, 47]. To offer a solution to this dilemma a comprehensive database was developed since 2009 at the Chair of Metal Forming Technology of the University of Kassel consistently aggregating commercially available market forecasts of global car production rates with additional streams of information specifically related to press hardening technology, e.g. body-in–white design, process technology, production capacities, product characteristics and patent applications, **Figure 27**. Due to the large number of different information streams and sources, the collected data are combined hierarchically either on a global or on a regional base grouped by different criteria (e.g. country, OEM, vehicle type, part category, etc.).

The evaluation potential of this database is demonstrated in the following by an exemplary analysis of the press hardening market, production capacities, ongoing innovation activities and the resulting demands until the year 2015.

It should be stated clearly that all data are aggregated from a very conservative perspective, in order to avoid any over-estimation!

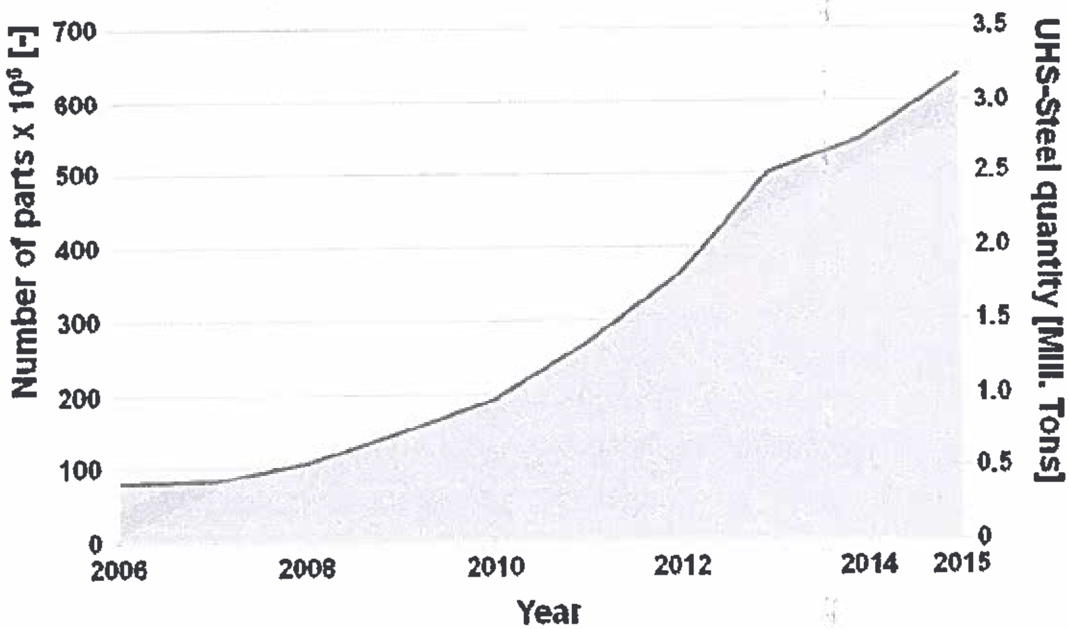

Figure 28: Development and forecast of global demand for press hardened components and pursuant the required quantity of UHS-steel for body-in-white applications

4.1 Market Monitoring and Market Forecast

An analysis of the global demand for press hardened parts based on this data base reveals an impressing evolution, **Figure 28**. Within only 5 years the amount of press hardened parts has increased from less than 80 Million parts in 2006 to almost 190 Million parts in 2010. The still ongoing progressive growth can be demonstrated by the fact that in time frame of only five years starting from 2011 a growth of almost 175% can be expected. That means that within only one decade the number of press hardened parts will have grown by a factor of 8.

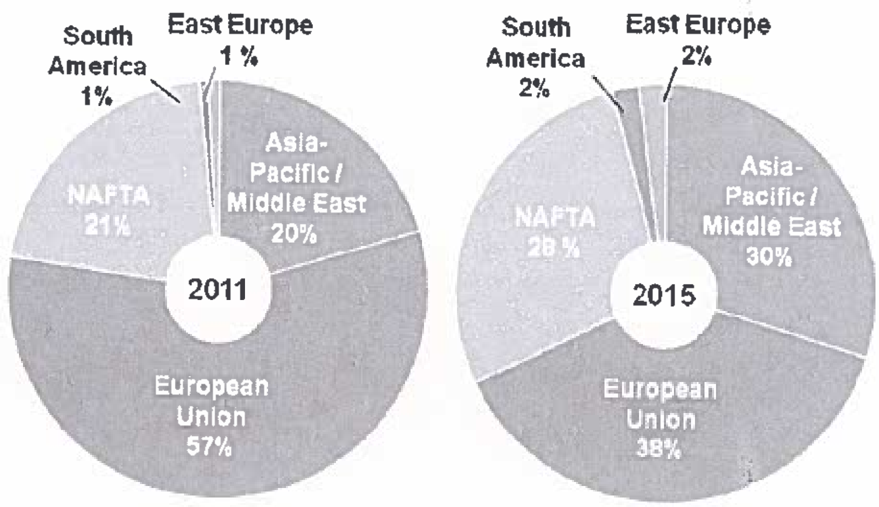

***Figure 29**: Regional market shares for the production respectively assembly of press hardened automotive parts (last database update: 31st of July, 2011)*

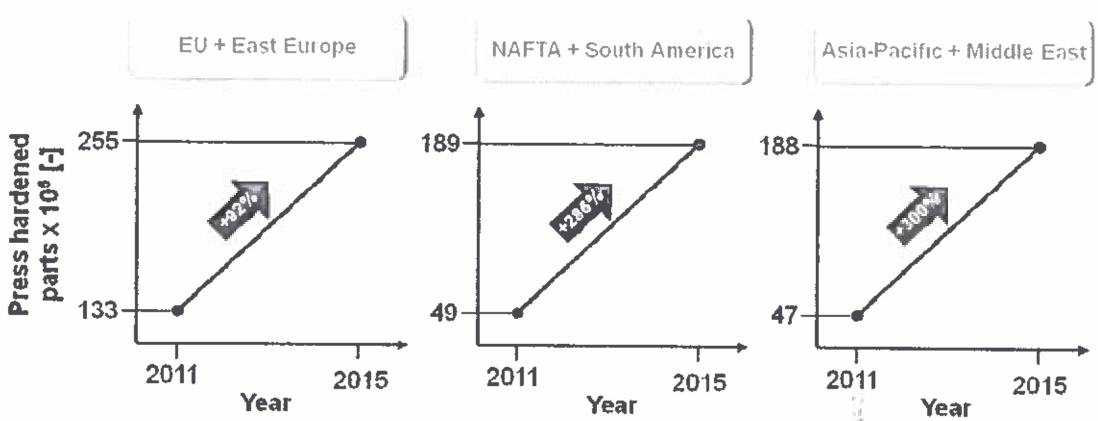

***Figure 30**: Regional market development for the production of press hardened automotive parts*

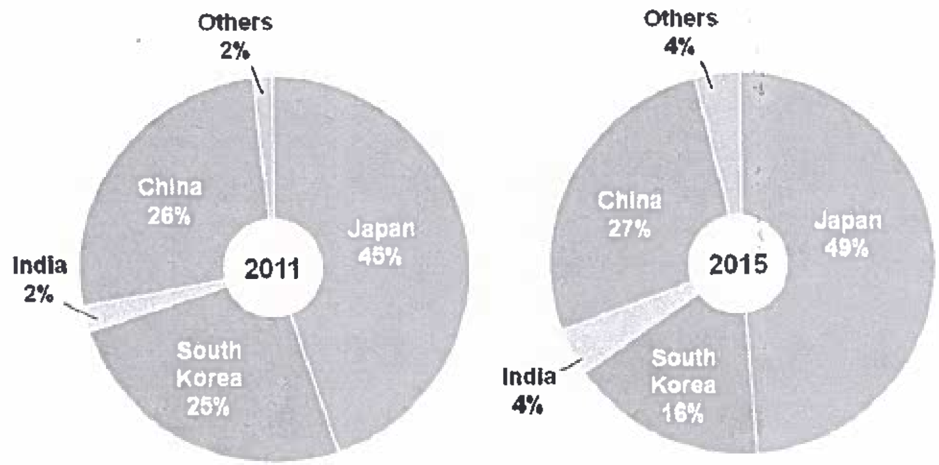

Figure 31: Development of the core-markets for the production and/or assembly of press hardened automotive parts within the Asian/Middle East region (last database update: 31st of July, 2011)

Under a regional perspective, the biggest growth can be expected in the Asian/Middle East region with an increase of market share of 10% between 2011 and the end of 2015, **Figure 29**, which corresponds to a total press hardening production and/or assembly of 188 Million parts in 2015, **Figure 30**. **Figure 31** differentiates between the individual shares of the core-markets within this region.

Due to a rising overall market share between 2011 and 2015 for the NAFTA region, **Figure 29**, an effective increase of production volume of 286% can be expected in the same period, **Figure 30**, finally reaching a market share of 28% in 2015, **Figure 29**; effectively, this means a production volume of 189 Million press hardened parts in 2015 in this region. The market share of the European Union gets lower between 2011 and 2015, **Figure 29**; however, also in this region the overall increase in production volume leads to an effective increase of 92% corresponding with a number of 255 Million press hardened parts, **Figure 30**. The alleged small markets in South America and East Europe should not be underestimated; 2% of market share for South America in 2015, **Figure 29**, means a production volume of nearly 13 Million parts.

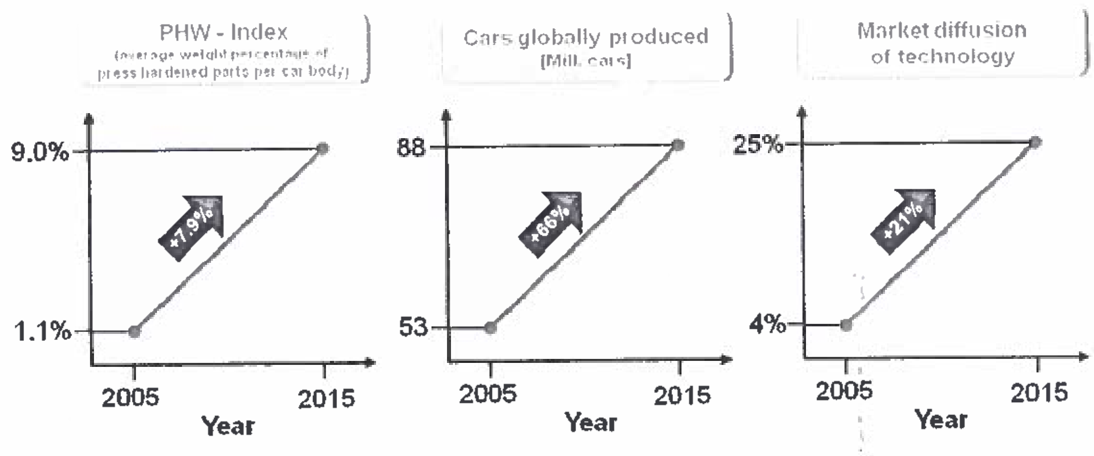

***Figure 32**: Indicators of market growth*

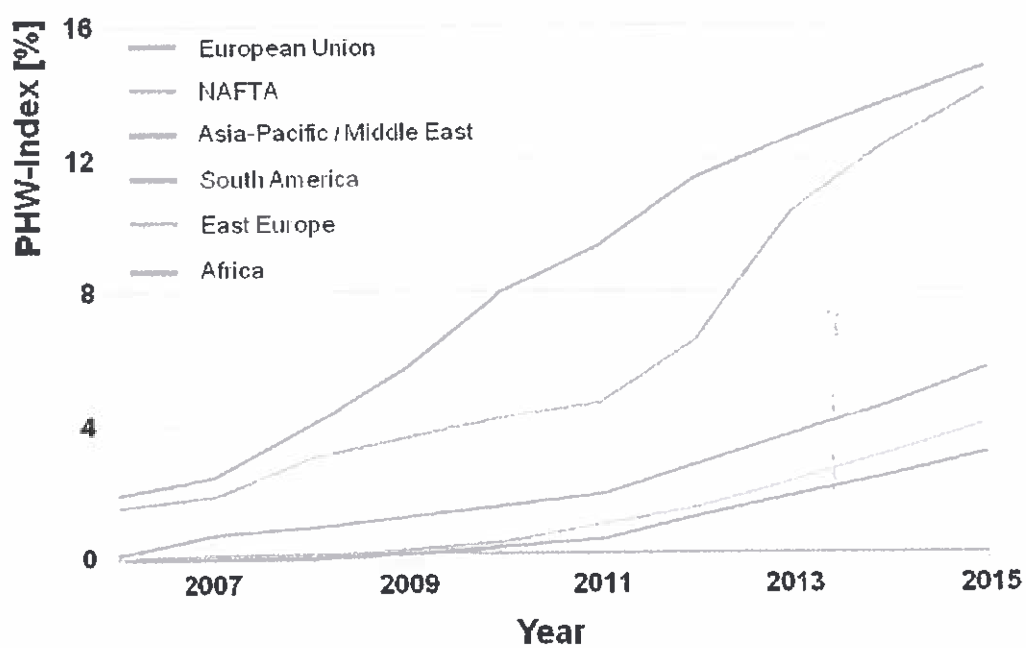

***Figure 33**: Regional development of weight percentage of press hardened parts per car body*

The main sources of this growth are the ongoing diffusion of press hardening technology in general, the increasing weight percentage of press hardened UHSS parts in body-in-white structures and the increasing number of globally produced cars, **Figure 32**. The intensity of these forces differs depending on local market requirements and constraints. **Figure 33** shows exemplarily the regional development of weight percentage of press hardened parts per car body. However, the underlying driving force remains, of course, the already aforementioned legal demand for drastically improved crash performance with at the same time reduced weight and, therefore, reduced CO_2-emission.

The previously mentioned substantially increasing quantity of parts subsequently requires a sufficient availability of blank material resulting in a steel consumption, which is displayed on the right axis in **Figure 28**; typical scrap rates for blanking operations were taken into account for determination of this data. Beyond the significant market growth for ultra-high strength heat treatable steels for press hardening application in general, it is the larger diversity of steel variants, especially with respect to the applied coatings (see 5.2), which actually encourages competitiveness in this market.

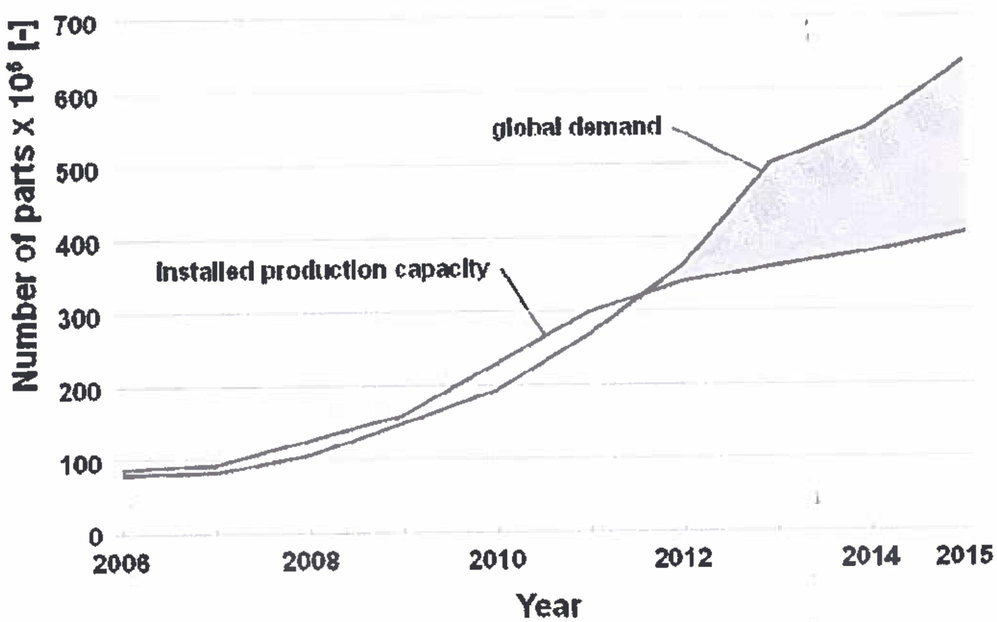

***Figure 34**: Production capacity versus demand*

4.2 Production Capacities

But not only may the availability of UHS-steels constitute a limiting factor for the future, also a sufficient availability of suitable production lines for hot forming operations has to be assured. Based on the number of installed production lines registered in the data base and under consideration of typical improvements in cycle time (see 5.2) and overall availability and process efficiency, global production capacity can be evaluated over time, **Figure 34**. It should be noticed, that for this evaluation only production lines for serial production were taken into account. Typical tryout lines and infrastructures for prototype production or testing were explicitly not counted for this elicitation. If, from 2011 on, globally available infrastructures would remain unchanged, a continuously growing capacity deficit inevitably would evolve, **Figure 34**, leading to a production undercoverage of 42% in 2015.

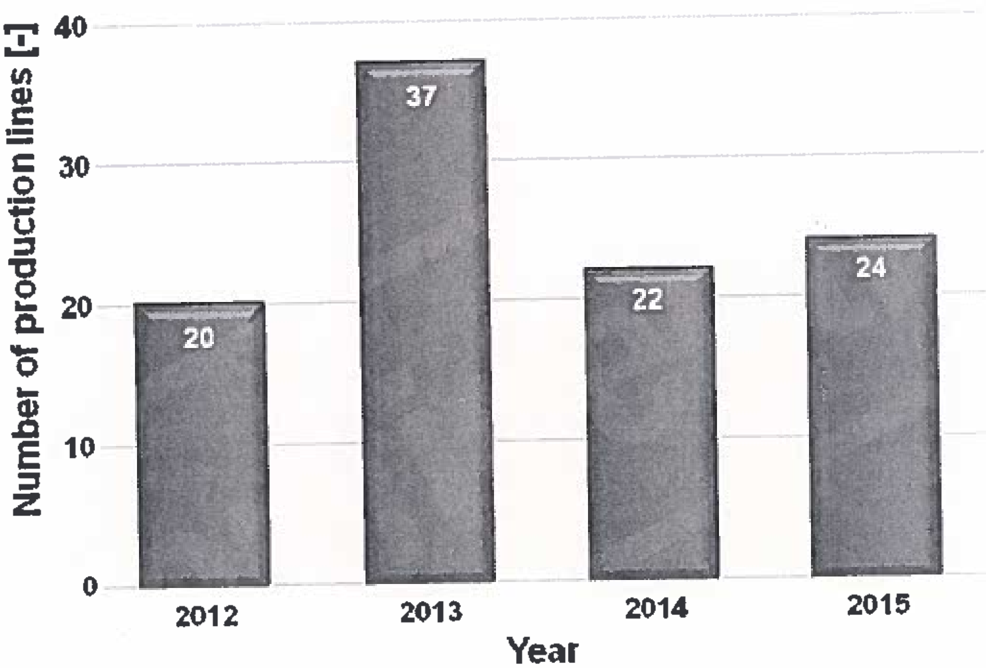

Figure 35*: Required production lines to close the gap between market request and installed production capacity*

Under the presupposition that, due to the previously mentioned ongoing substitution, this identified capacity gap will be and, from OEM perspective, has to be completely closed, the amount of required new production lines per year are calculated, **Figure 35**. Especially the year 2013 shows a substantial need for new production capacities, which may lead to temporary supply bottlenecks, if the investment activity does not follow the actual need. It can be expected that at the end of 2015 in total 238 press hardening lines will be in operation for industrial serial production, which then finally constitutes an increase of installed lines of 116% since 2010, **Figure 36**. Under the aforementioned assumption of predominating local supply, the regional distribution of production lines can be estimated on the basis of the regional shares given in **Figure 29** and **Figure 30**.

Figure 36*: Until the end of* 2013 *globally installed press hardening production lines for automotive serial production*

Due to effective supply chain management, it is expected that most of the necessary investments will take place near to countries or in countries with distinct high growth rates in the production of press hardened parts. Under this assumption, from the total number of 103 press hardening production lines additionally to be in operation until the end of 2015, 35% have to be installed in the NAFTA region and also 35% in the Asia/Middle East region. It has to be mentioned, that the huge investments in further press hardening production capacities especially in the European Union, which already have been decided and will be operational still in 2011 are counted as existing capacities and, therefore, are explicitly not covered by this forecast. However, also in Asia and the EU region quite some additional lines are operational for serial production in 2011; compared to the situation at the end of 2009, 8 additional production lines are in operation in Japan and 3 in South Korea, in India 2 additional lines were installed in the mean time.

Actual delivery times for typical series production equipment of up to 20 months reveal another important deficit, which has to be solved in advance of any installation: a *decision deficit*! The pursuant urging strategical investment decisions on building up the required production capacities have to be taken until the end of **2015**.

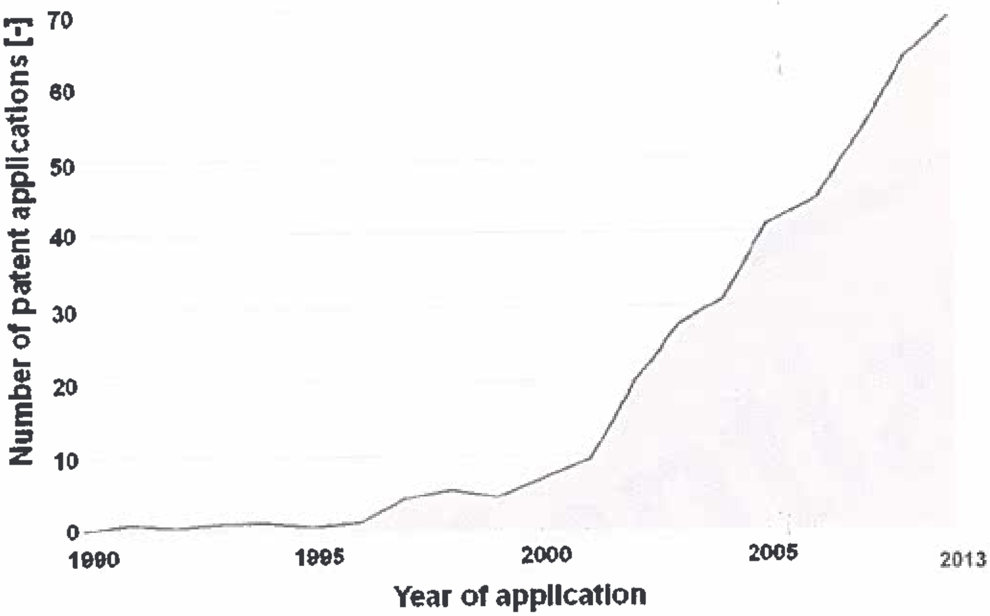

***Figure 37**: Patent applications in press hardening technology*

4.3 Innovation strategies

Another way to forecast future trends in the press hardening market is to investigate global and local innovation strategies, in order to identify technological driven market trends for example by a structural patent analysis [48-50]. Due to the implemented global patent research, all patent applications with direct relationship to press hardening of manganese-boron steels can be analyzed directly from the data base. Multiple patent applications for one innovation, also known as so-called patent families, were counted as one patent. In this research, only applications up to 2009 were considered because available data for 2010 are incomplete, due to the time difference between application and publication date. **Figure 37** shows the number of patent applications over time until 2009. While until 2001 a steady but very moderate increase can be observed, the number of applications growths significantly since that time, finally indicating intense ongoing innovation activities.

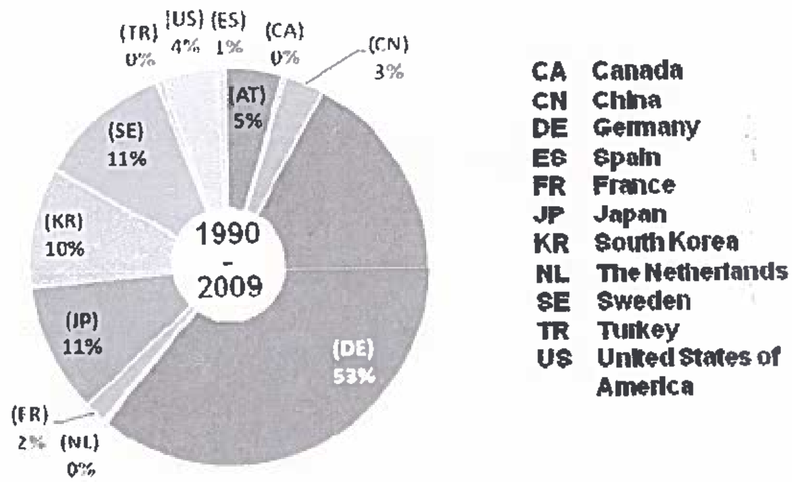

***Figure 38**: Applicant home countries of press hardening related patent applications between 1990 and 2009 (last database update: 31st of July, 2011)*

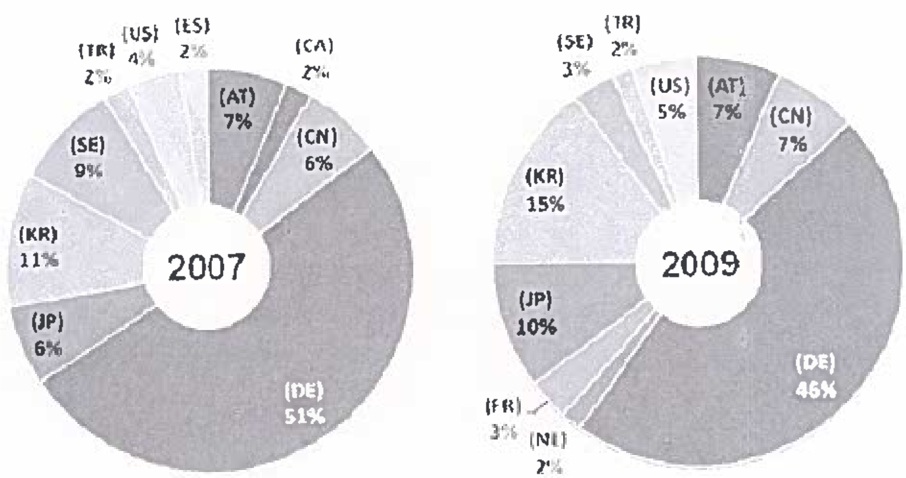

***Figure 39**: Comparison of applicant home countries difference between 2007 (left) and 2009 (right)*

A home country analysis of applied patents reveals international focal points of these activities showing the level of supply chain globalization and indicating local availability of know-how [50]. Considering the time period from 1990 to 2009, German companies held a dominant position with 53%, followed by Sweden and Japan with 11 % each and South Korea with 10%, **Figure 38**. However, a comparison between 2007 and 2009, **Figure 39**, also shows an ongoing shift in the applicant home countries and, therefore, reveals long-term changes in technological ranking. For instance, while for Germany a reduction of filed patent applications from 51% down to 46% can be noticed within the evaluated period of only two years, a total growth from 23% up to 32% can be observed for the main Asian industrial countries, i.e. Japan, South Korea and China.

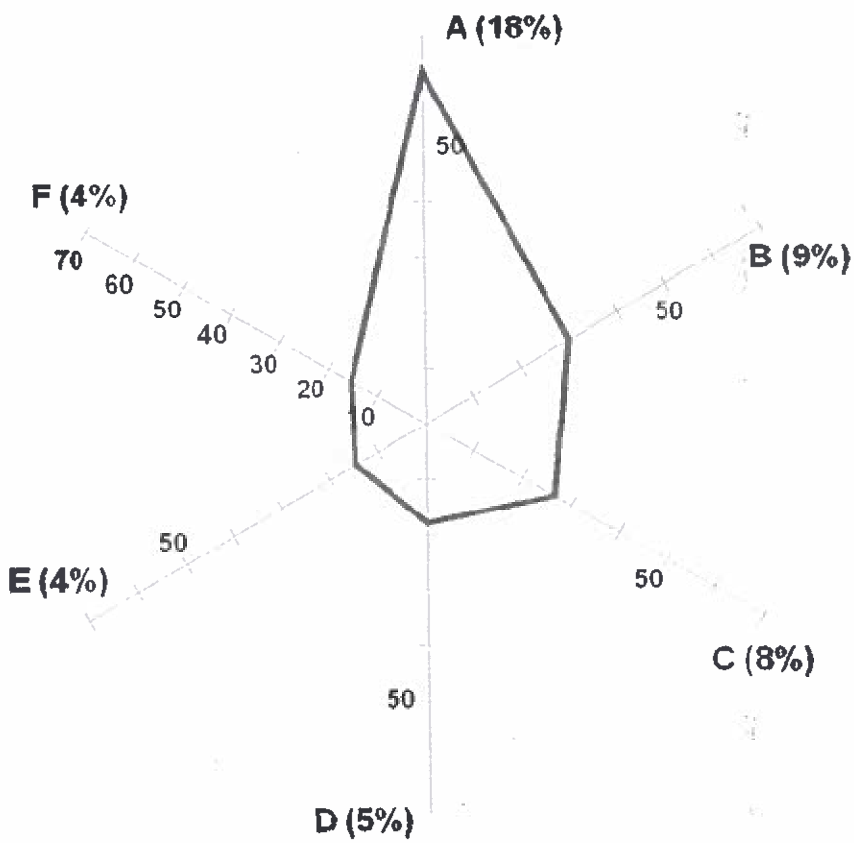

***Figure 40**: Ownership of patents in press hardening and related technology*

With respect to the individual ownership of patents, it becomes obvious that almost 50% of all mother patents are held by only six legal entities, **Figure 40**. Regarding the resulting technological ranking between competing companies, it is interesting to notice that number one holds twice as much patents as number two.

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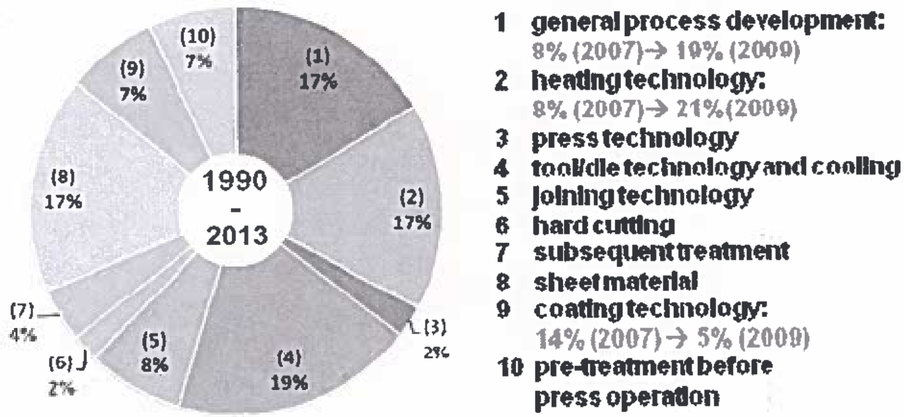

,***Figure 41****: Corresponding sub-technologies until the year* .**2013**

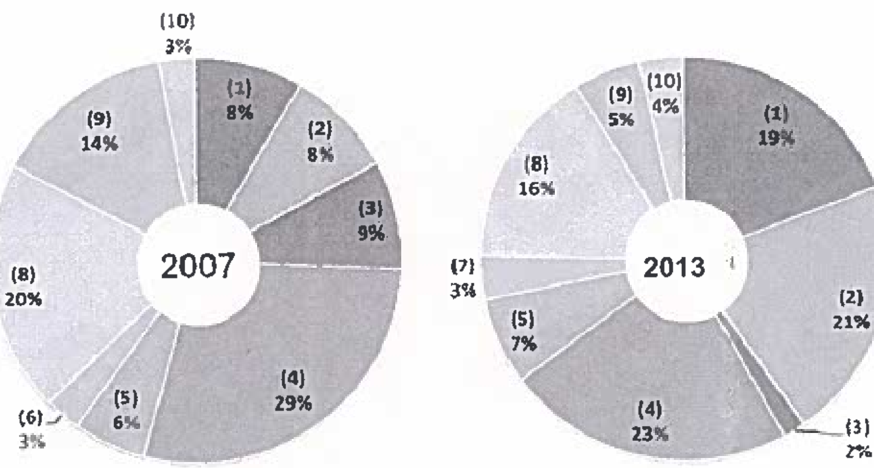

Figure 42*: Corresponding sub-technologies 2007 versus* **2013**

The identification of "white spots" on the technological "map" is essential when it comes to define Research and Development activities, which finally aim at gaining unique selling points [48, 50]. With respect to this, the database allows to differentiate between several clusters of sub-technologies. To accomplish this, every patent is assigned to a specific corresponding sub-technology specified in **Figure 41**. A subsequent evaluation allocates the distribution of related sub-technologies of all applied patents until **2013** in direct relationship with the corresponding press hardening technology, **Figure 41**. It can be shown that most of the patented innovations are related with tool/die and cooling technology (19%), which underlines the key role of e.g. high conductive tool steels, alternative cooling concepts, management and intelligent control of active elements in dies as well as lifetime and thermal management of dies. It is followed with 17% by innovations in heating technologies and sheet material developments like microstructure customization, chemical composition etc. Likewise is the innovation activity in the field of general process development for example of alternative process routes and new process combinations. Technologies like hard and warm cutting, innovative press technologies and subsequent treatment are underrepresented. This is an indicator for minor innovation activities or for the presence of a strong major patent [50].

A comparison of the applied patent technology fields between 2007 and 2013 shows a change of the innovation focus of the involved companies over the last years, **Figure 42**. A significant rise in the importance of different technologies for example heating technology (8% in 2007 up to 21% in 2013) or general process development (8% in 2007 up to 19% in 2013) is observed. On the other hand, also a massive reduction can be shown for surface coating technologies (14% in 2007 down to 5% in 2013). A refocus of technology-lifecycle triggered innovation priorities can be identified as main driving force behind this trend. For example increase in heating-technology related innovation can be attributed to the aim to reduce cycle times in heating, to increase energy efficiency, to develop solutions for tailored heating strategies and to increase overall efficiency.

The particular aspect of *tailored* (= graded) *part properties* combined with press hardening technology appears to be one of the major technological trends (see. 5.1). **Figure 43** reveals the increasing number of patent applications filed especially since 2005 in this particular field.

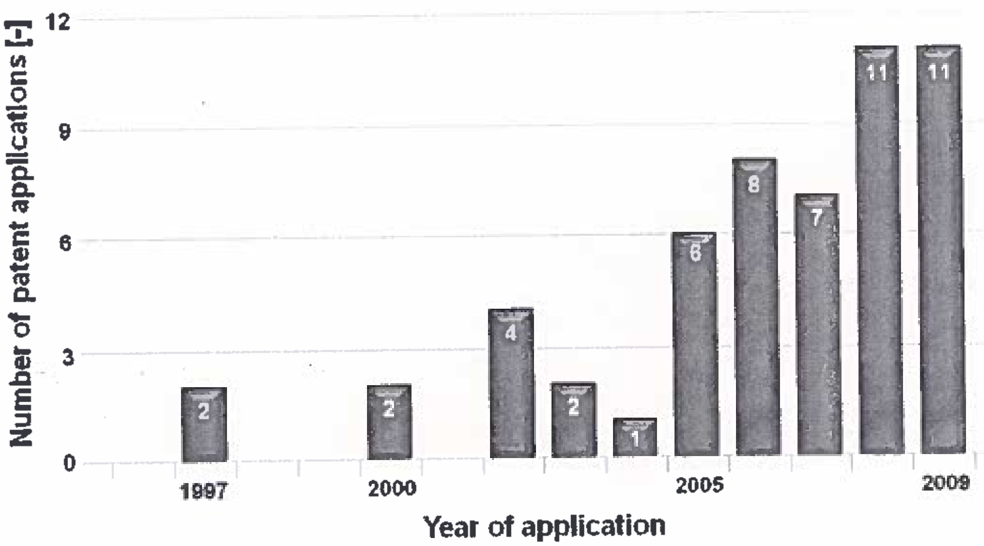

Figure 43: Patent applications with particular relation to tailored part properties adjusted by press hardening

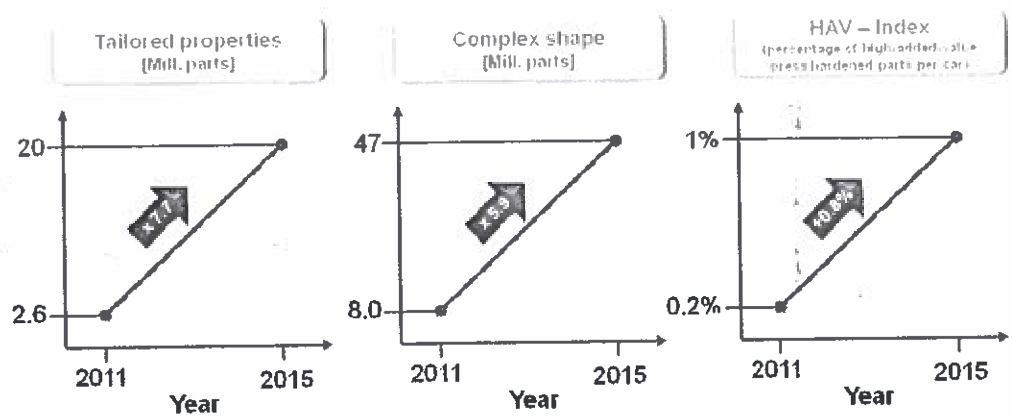

Figure 44: Development of high-added-value parts produced by press hardening

Generally, a continuously ongoing differentiation between commodity parts on the one hand, and high-added-value parts, on the other hand, can be observed for a considerable time. The aforementioned parts with tailored properties typically contribute to a higher added technological value, which finally also leads to a higher added commercial value. Another important value trigger in hot stamping is constituted by the shape complexity of the part. According the data base, an increase of overall share of 0.2% high-added-value press hardened parts per car body in 2011 up to 1% in 2015 can be expected, **Figure 44**. As already for the PHW-Index in **Figure 33**, also the HAV-Index differs due to local market requirements and constraints, **Figure 45**.

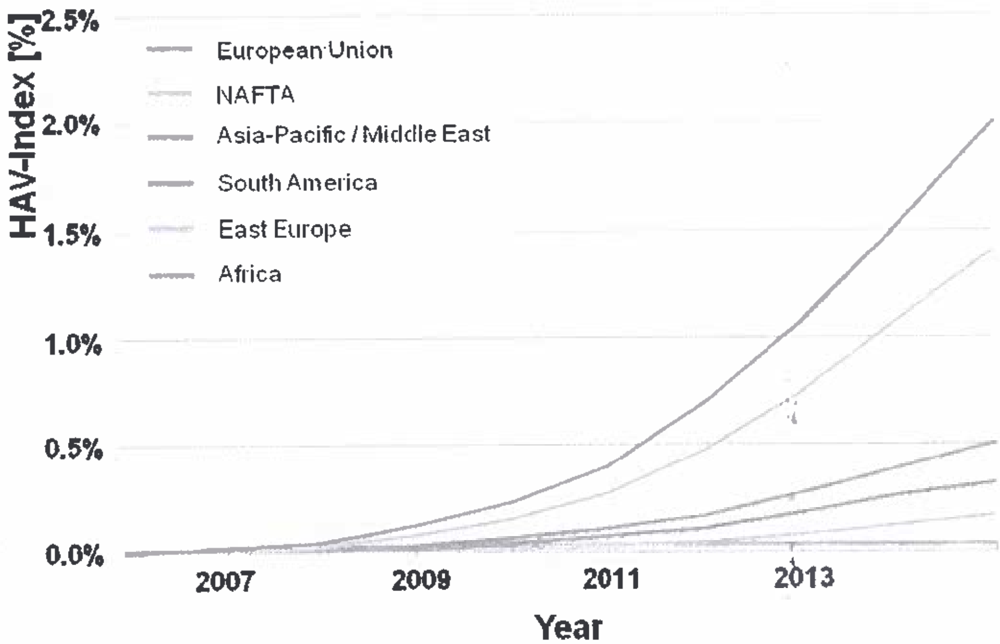

***Figure 45**: Regional development of high-added-value press hardened parts per car body*

Assuming that on its way to reaching technological maturity press hardening, as many other innovations, follows a characteristic S-type course [48-51, 54-56], it is comprehensible that in the actual premature phase process innovations dominate. However, with progressing maturity, these process related activities will be increasingly replaced by product related innovations utilizing the already available potential of press hardening process technology.

5 Trends and Perspectives - *"What we can expect for tomorrow"*

Actual research and development activities address two major target areas:

- development of new materials, design principles and products
- improvement of process efficiency.

Figure 46 differentiates the sub-targets assigned to these areas.

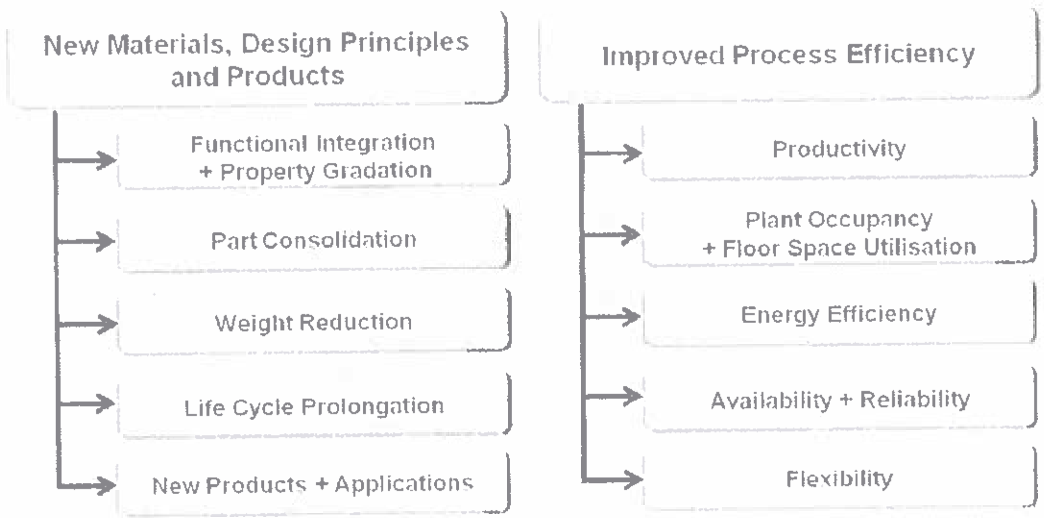

***Figure 46**: Target areas for research and development in press hardening technology*

5.1 New Materials, Design Principles and Products

From a functional point of view, press hardened parts have to contribute to a complex crash management of the body-in-white structure. Coming from that, it becomes obvious that just showing an ultra-high level of strength and, therefore, maintaining sufficient intrusion resistance and preserving structural integrity under typical crash load, constitutes only one aspect of such functionality. Another important aspect doubtlessly is constituted by a sufficient ability to absorb impact energy by a controlled plastic deformation within the structure. While highest strength is an intrinsic property of a press hardened part directly resulting from the martensitic phase transformation, a high level of ductility, which is unavoidably necessary for the desired plastic deformation, unfortunately, is not an intrinsic property. Several approaches to achieve a defined strength-ductility distribution over the overall part geometry are known [30-32]. A secondary target of leaving defined zones over the part geometry unhardened consists in the reduction of cutting forces and, in further consequence, of the risk of failure by residual stress induced cracks as a result of an interference of accumulated stress load during trimming and subsequent welding.

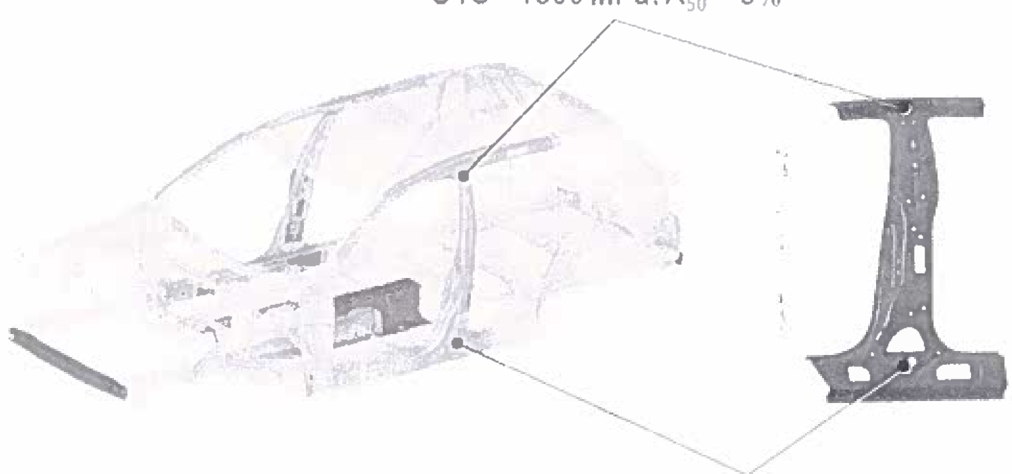

***Figure 47**: First series application of a thermo-mechanical tailored B-Pillar produced by differential heating (source: Volkswagen AG)*

Figure 47 shows a body-in-white structure with a thermo-mechanically tailored monolithic B-pillar consisting of an ultra-high strength upper part and lower part with increased ductility and, of course, reduced strength. In this case, the property gradation is based on a locally and temporally variable temperature field adjusted during heating before forming, **Figure 48**. By controlled intermediate cooling of the lower part before being transferred to the press, a full martensitic transformation can be avoided during subsequent forming and rapid closed-die cooling. In this zone, therefore, a ferritic-perlitic phase composition evolves, exhibiting the desired higher level of ductility.

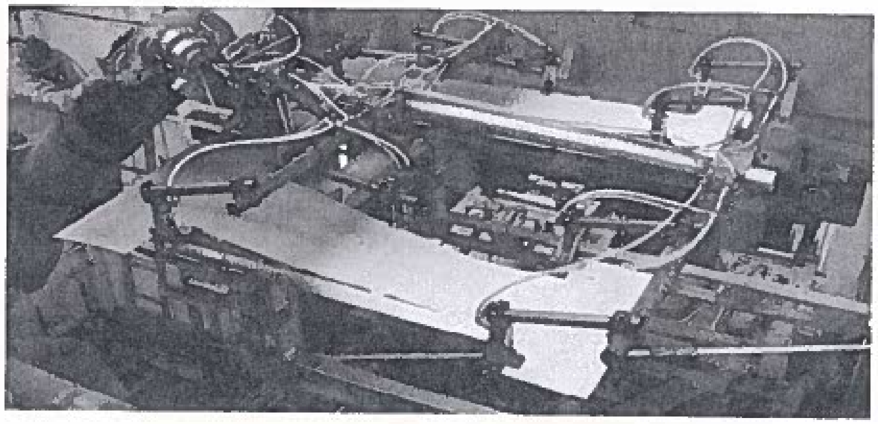

Figure 48: *Differentially heated blanks to be transferred from the furnace to the press for subsequent forming and partial hardening (source: Volkswagen AG)*

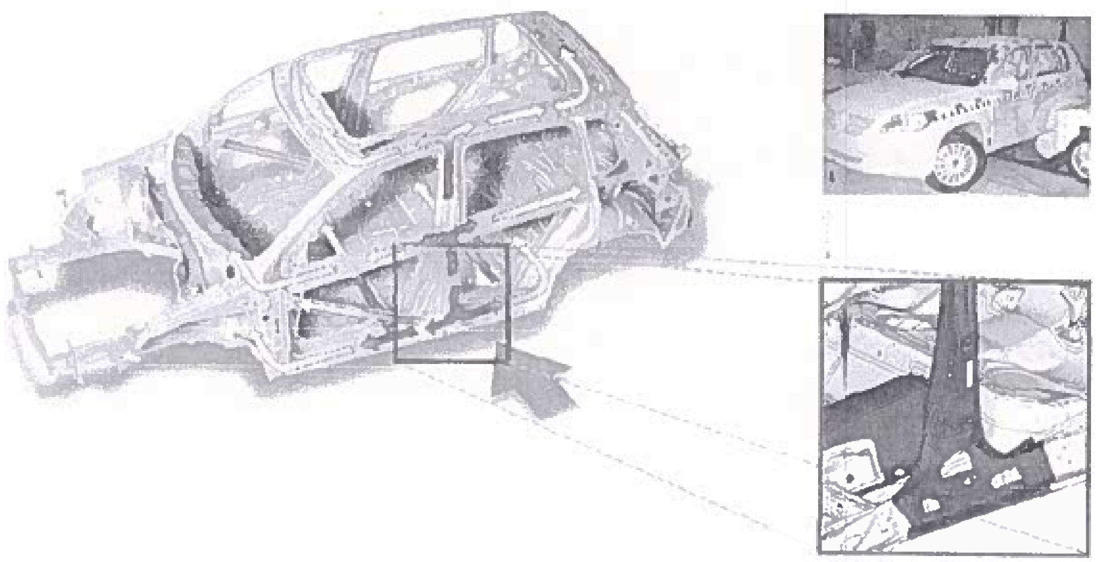

Figure 49: *Load path during side crash (left) and characteristic deformation behavior (lower right: crash simulation; upper right: real crash test scenario) of a thermo-mechanically tailored B-pillar (source: Volkswagen AG)*

The characteristic plastic deformation behavior of a thermo-mechanical tailored B-pillar under crash load is explained in **Figure 49**.

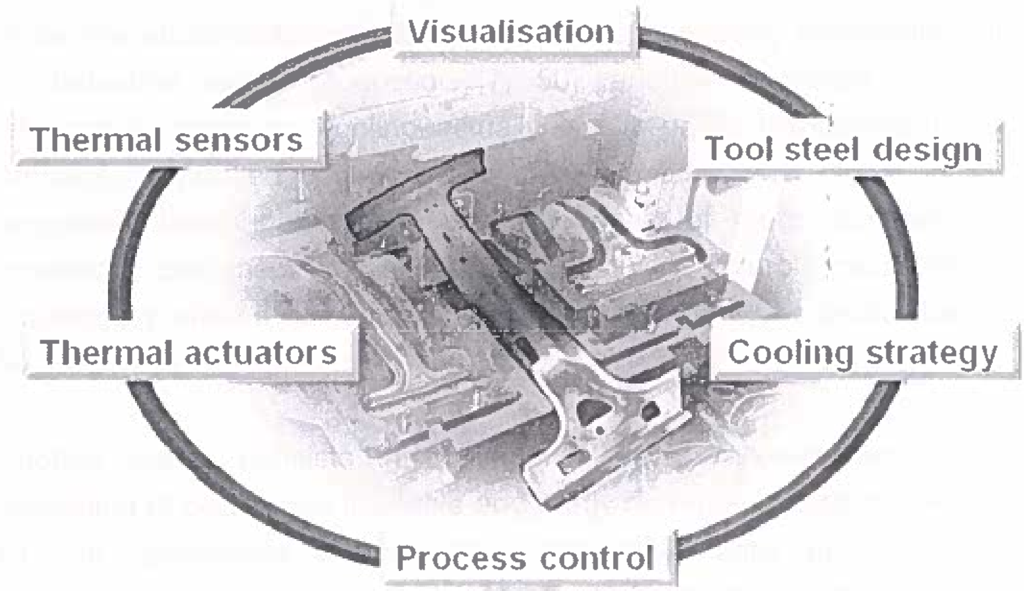

***Figure 50**: Design elements of an "intelligent" tool system to produce tailored parts by differential cooling during press hardening*

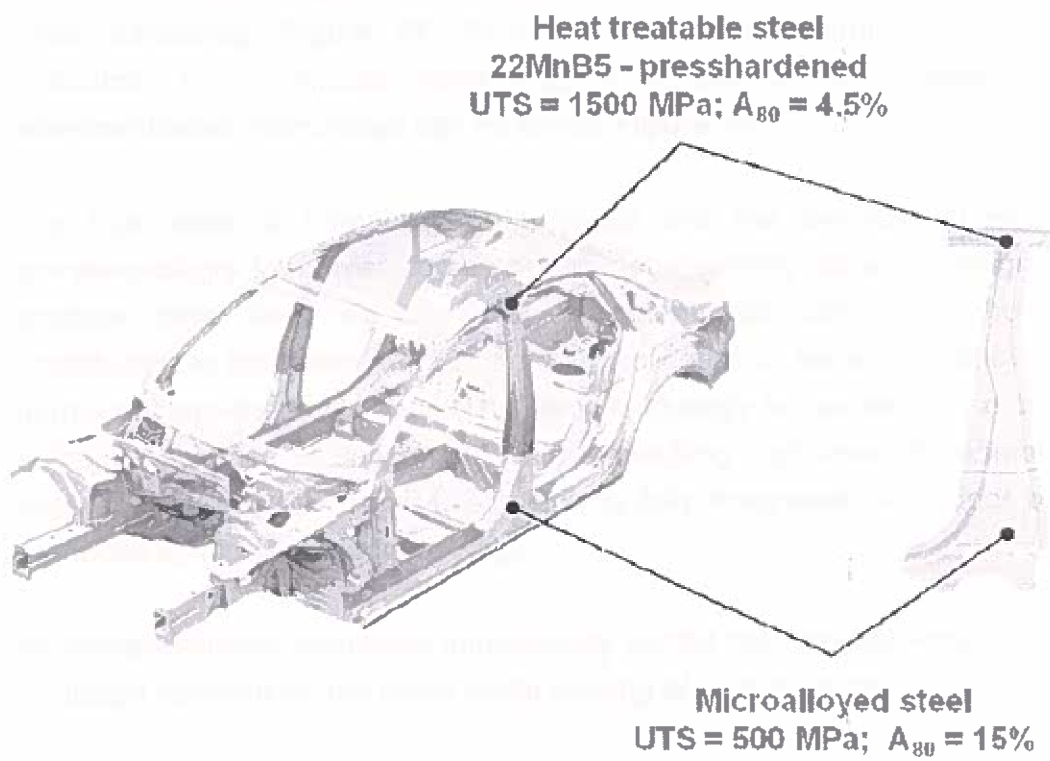

***Figure 51**: Application of tailor-welded blanks for the production of press hardened parts with graded properties (source: Audi AG)*

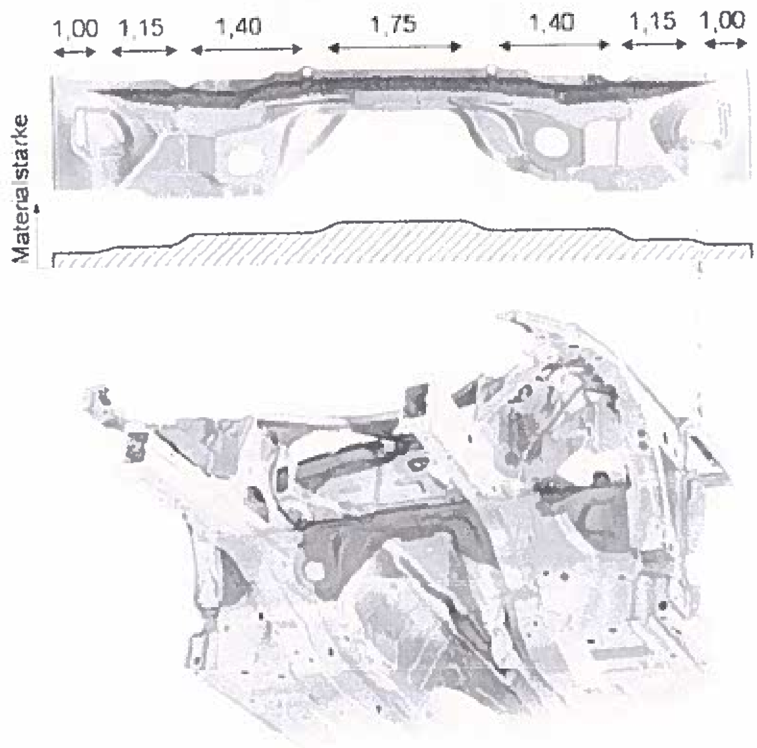

***Figure 52**: Application of press hardened tailor-rolled blanks for press hardening of a subplate (source: Audi AG)*

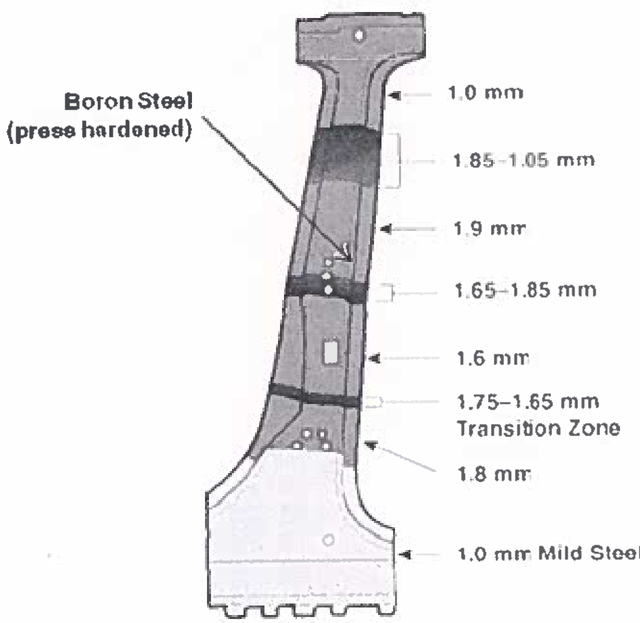

***Figure 53:** Application of combined tailor rolled + tailor welded blanks for weight reduction + property gradation*

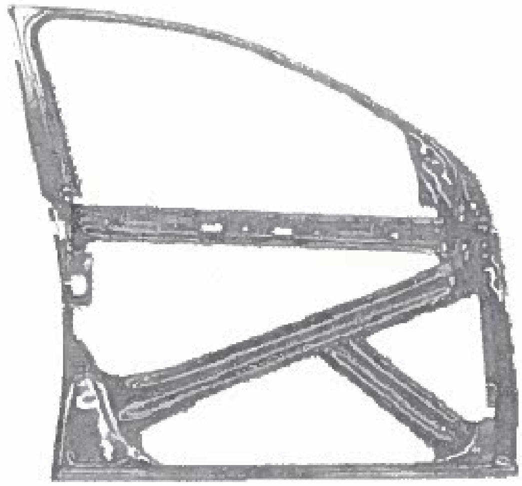

***Figure 54**: Fully integrated inner door panel produced by direct press hardening (source: Braun CarTec GmbH)*

Among all activities actually aiming at improved material properties, the availability of galvanized UHSS which performs robust and reproducible at direct press hardening and, at the same time, provides sufficient cathodic corrosion protection has doubtlessly highest priority [61, 62].

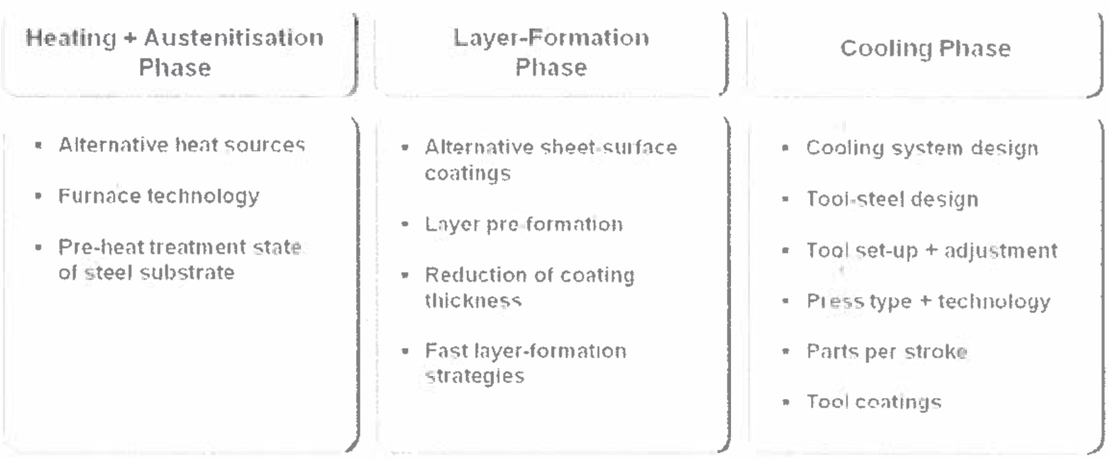

***Figure 55**: Measures to improve process efficiency*

5.2 Improved Process Efficiency

While the main trend in the first area obviously is constituted by the production of parts with tailored properties, activities in the second area are concentrating on a significant shortening of process time and. In this context, several approaches can be identified, **Figure 55**. Since in a typical process cycle, heating covers the main time consumption, many efforts are actually invested to bring down heating time. Among these, alternative sources for fast heating strategies [63] can be considered in the same way as important as strategies for shortening of the layer-formation phase [61, 63] and closed-die cooling phase [53]. Also cutting and trimming of press hardened parts typically being on a tensile strength level beyond 1'500 MPa still constitute a real challenge leaving a huge potential for further development as well for hard as for warm trimming as for LASER-trimming actually nearly unexploited.

Nevertheless, some remarkable improvements regarding heating, cooling and also subsequent LASER-trimming already could be achieved only within a five-year period since 2007, **Figure 56**.

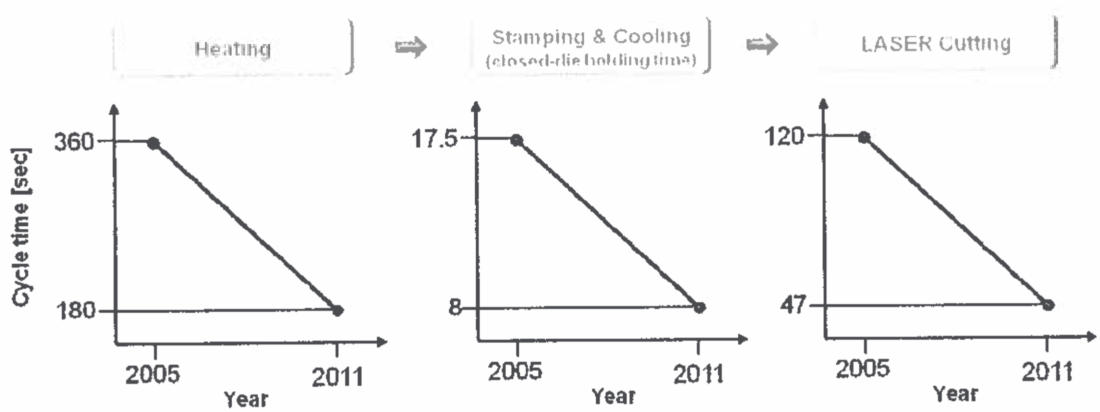

***Figure 56**: Improvement in efficiency over the process chain for the production of press hardened parts.*

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