HOT FORMING:
Crucial Technology for Lightweighting of Sheet Metal Components

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> The process benefits manufacturers by providing lightweight and strong crash-resistant parts.

INTRODUCTION

Automotive OEMs and suppliers face tough challenges regarding vehicle weight reduction and its impact on fuel consumption, carbon dioxide (CO_2) emission limits and manufacturing costs. According to U.S. corporate average fuel economy (CAFE) regulations, automakers are required to produce vehicles with higher fuel economy of 54.5 mpg by 2025. At the same time, according to European Union (EU) CO_2 standards, by 2021, new cars in Europe should emit no more than 95g/km of CO_2 [1]. The National Highway Traffic Safety Administration (NHTSA) sets standards for vehicle safety, such as those for impact resistance, restraints and fuel economy.

Testing done by the Insurance Institute for Highway Safety (IIHS) has also encouraged improved frontal, side and rear impact ratings, as well as roof strength and rollover ratings for automobiles on the road today. Meeting these standards often require additional weight. While adding massive safety components, automakers struggle to reduce weight and improve efficiency to meet increasing CAFE standards. Apart from these regulations, fuel economy and safety targets are becoming even more important from the consumers' point of view, as consumers expect more fuel economy and safety in the next car they purchase than the last one they owned.

Vehicle manufacturers have a number of options when it comes to improving fuel efficiency, and they will need to pursue most of them to meet the new tough standards. For example, they can work on improving the fuel economy of current internal combustion engines (ICEs), maybe by introducing new designs or by pairing them with transmissions that are more efficient. Another option for OEMs is to introduce new types of powertrains, such as hybrid or electric vehicles. The OEMs can also improve vehicle aerodynamics to reduce drag and boost fuel efficiency. Last but not the least, automakers can also take steps to shed some weight from the vehicles by introducing lighter, stronger materials, reducing the number, size and weight of components via new designs or new manufacturing techniques [2].

Let's assume that we have all the resources available to build a highly fuel-efficient vehicle that will have a very economical ICE coupled with a lithium ion battery and motors to make a hybrid powertrain, and a car design with the least possible drag coefficient. Even with all these resources, it will still be questionable to build a highly fuel-efficient vehicle if the overall weight of the car is hefty. This is the reason why lightweighting of automobiles becomes one of the most important criterion for improving fuel efficiency, as well as reducing CO_2 emissions. Heavier vehicles have greater inertia and greater rolling resistance, which contribute to increased fuel consumption. Reducing weight is a very effective way to improve a vehicle's efficiency.

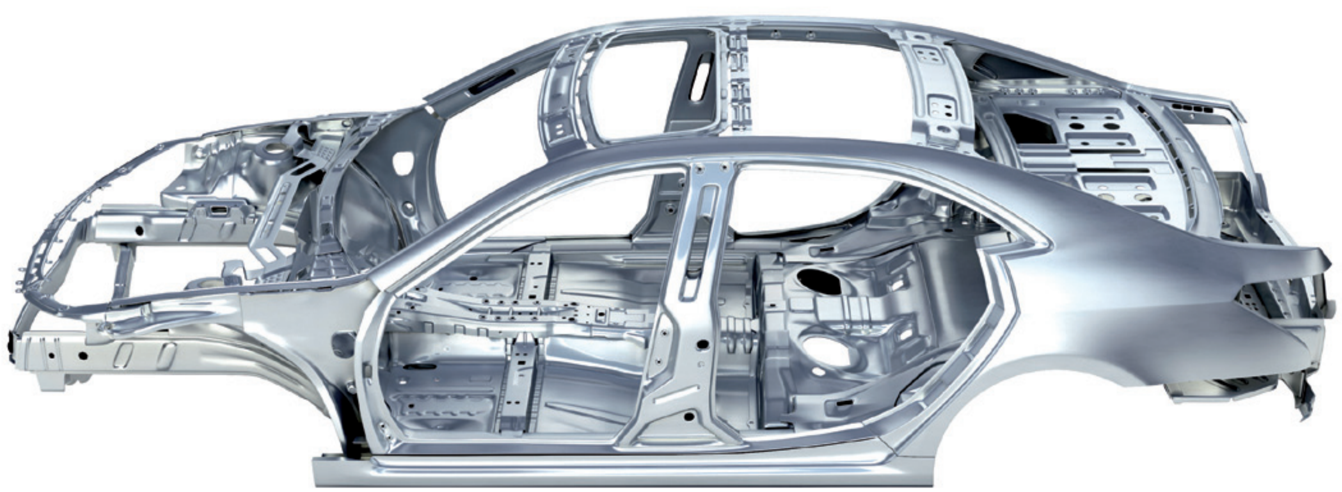

FIGURE [1] / Automotive body-in-white (BIW)

A recent study found that for every 100-kg reduction, the combined city/highway fuel consumption could decrease by about 0.3 L/100 km for cars and about 0.4 L/100 km for light trucks. Also, a recent Massachusetts Institute of Technology study estimates that vehicle weight reductions of 35 percent could be implemented at a reasonable cost. Vehicle weight reductions of this magnitude could lower fuel consumption by 12 percent to 20 percent with no sacrifice in current vehicle safety and performance [3]. The Energy Department, on the other hand, says that reducing a car's weight by only 10 percent improves fuel economy by 6 to 8 percent.

Not only gas- and diesel-powered vehicles, but electric vehicles (EVs) benefit from lightweighting in a number of ways and could offset some of the extra weight that the battery adds. Engineers and scientists are constantly trying to build lighter and more efficient powertrains for EVs. Lightweighting can certainly improve their driving range per charge, which is often considered the biggest hurdle for EV manufacturers.

Lightweighting, also known as weight reduction or mass reduction of vehicles, constitutes one of the greatest challenges to the automotive industry. Lightweighting becomes even more challenging when automakers have to make components lighter and at the same time stronger. The Body-in-White (BIW, Figure 1) is the stage of manufacturing during which the unpainted sheet metal components are welded together to form the vehicle's body and accounts for approximately 50 percent of weight-saving potential. In today's car-body engineering, the primary materials are aluminum, high and advanced high-strength steels and carbon fiber. A successful lightweighting strategy involves much more than simply replacing a few steel panels with aluminum or carbon fiber. It's about using the right material for the right part in the right place. Lightweighting has become a whole-vehicle concept in itself, improving not only fuel economy and safety, but also vehicle performance and handling.

BIW MATERIALS

Three materials that show promise in lightening vehicles are high-strength steel, aluminum and carbon fiber composites. About 60 percent of the average car by weight is steel in one form or another. Since 2000, the industry has doubled the available grades of steel and increased strength levels by 50 to 100 percent. The steel available for car companies now is up to five times stronger than steel used 10 years ago. It is true that steel does not yet offer the same weight saving as aluminum, but it is pretty close and significantly cheaper.

Carbon fiber (CF), on the other hand, remains the lightest, strongest, but at the same time, very expensive as compared to steel or aluminum. Current costs of CF are five to six times as high as steel, assuming a mass production of 60,000 units per year. Another hurdle for carbon fiber is the slower production process, affecting the mass production [4]. Over the next two decades, however, there are chances of significant cost reductions for automotive carbon-fiber applications. Even after all this, the cost of carbon fiber is estimated to remain higher compared to steel and aluminum, making it less attractive for the mass market, as shown in Figure 2.

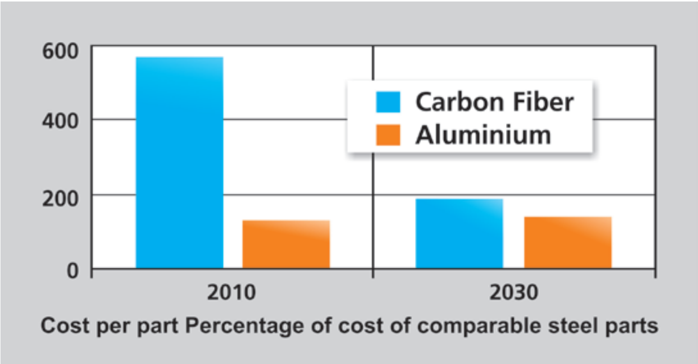

FIGURE [2] / Cost comparison – Al vs CF [5]

Advanced High Strength Steel (AHSS) and Ultra High Strength Steel (UHSS) uniquely satisfy safety, efficiency, emissions, manufacturability, durability and cost requirements. Key reasons for using AHSS is better performance in crash-energy management and superior strength, allowing this performance to be achieved with thinner materials, resulting into lower vehicle weight. The whole idea of lightweighting started as a way to increase the mpg of vehicles so that the emissions can be reduced and hence the greenhouse gas (GHG).

Low-density materials like aluminum, magnesium and composites—often used in automotive lightweighting—can produce 7 to 20 times more emissions as compared to steel during production [6]. This kind of unintended consequence is an issue today, and it will only get worse if the focus remains solely on tailpipe emissions. Therefore, using low GHG materials such as steel becomes even more important. Another advantage is steel's 100-percent recyclability, making it the most recycled material on our planet. In 2014, the combined average use of AHSS and UHSS in North America to produce light vehicles was 254 pounds, and it is expected to nearly double to 483 pounds by 2025, as shown in Figure 3. Most steel companies are extending their research and development efforts to expand the range of properties available through these new steels to enable safe and environmentally friendly vehicles.

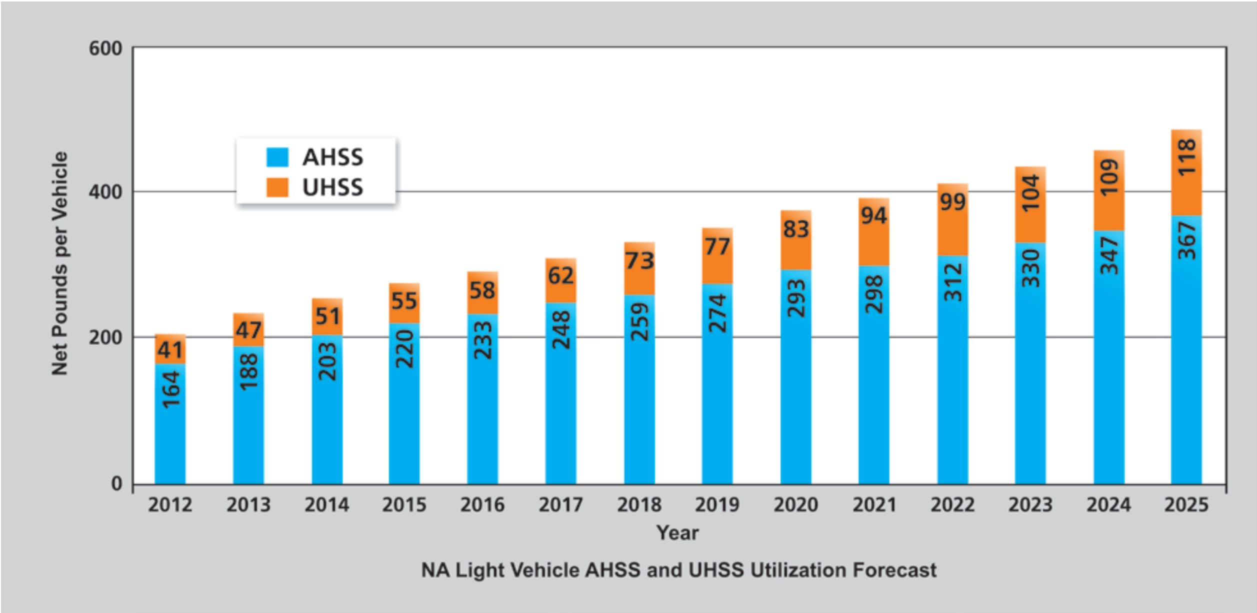

FIGURE [3] / Fast growing automotive steels [6]

AHSS was developed partly to address decreased formability with increased strength in conventional steels. As steels became stronger, they became more difficult to form into automotive parts. AHSS, although much stronger than conventional low to high strength steel, also offers high work-hardening and bake-hardening capabilities that allow increased formability and opportunities for part geometries optimization. Some types of AHSS have a higher strain-hardening capacity resulting in a strength-ductility balance superior to conventional steels. Other types have ultra-high yield and tensile strengths, and show a bake-hardening behavior. The bake-hardening effect is the increase in yield strength resulting from elevated temperature aging after pre-straining. Maximum part complexity usually requires superior stretch ability as evidenced by high work-hardening capability.

Increasing the strength of the steel reduces the stretching capacity of the steel because the work-hardening exponent (n-value) decreases with increasing strength for each type of steel. Not to mention, springback problems multiply as the yield strength rises. A crucial technology for lightweighting could be the implementation of press hardened steel (PHS) manufacturing processes, which were developed in the 1970s in Sweden and was first used by Saab Automobile in 1984. PHS, or hot forming, has steadily increased in popularity, and the use of hot-formed AHSS and UHSS components has rapidly increased. The number of production stampings from hot forming went from 3 million per year in 1987 to 360 million per year in 2015, and continues to rise in all regions of the globe [7]. For some new vehicles, the percentage of the hot-stamped steel components is close to 25 percent of the BIW weight [6]. Today, hot forming is used for stamping geometries with relatively complex shapes such as A-pillars, B-pillars, front- and rear-side members, cross members, roof rails, bumpers, door intrusion beams, etc.

HOT FORMING

Hot forming is a non-isothermal forming and heat-treating process for sheet metals, where forming and quenching

FIGURE [4] / Application of hot stamped parts in automotive BIW

(rapid cooling of the hot part) take place in the same step. Hot forming is also known as hot stamping, hot press, press hardening or die quenching. Hot forming is accepted as a viable alternative solution and widely used for UHSS and AHSS parts, which are difficult to form at room temperature because of the low formability, considerable springback and vulnerability to cracking during forming.

This process takes advantage of the low flow stress of boron alloyed steel (22MnB5) in the austenitic phase at elevated temperature and allows manufacturing parts with ultrahigh strength, minimum springback and reduced sheet thickness. In this process, a blank usually made from boron steel is heated up in a furnace to its austenitization temperature of around 900 to 950 degrees Celsius. The heated blank is then formed in an internally cooled die set and quenched under pressure at a minimum cooling rate of 27 degrees Celsius per second. This minimum cooling rate ensures the formation of a martensitic microstructure in the part, imparting high strength that is usually exceeding 1500 MPa. This means that it is possible to construct components with thinner gauges, and parts with complex geometries can be produced with minimal springback.

The hot-forming technology has been used to a good extent by Volvo in its second-generation XC90. Volvo used hot-formed boron steel to produce the vehicle's passenger safety cage. The material amounts to around 40 percent of the XC90's total body weight, which is approximately five times more than the first-generation XC90. As a result, the second-generation XC90 is 48 pounds lighter than its first-generation counterpart, despite being significantly larger, possessing improved safety features and demonstrating better noise, vibration and harshness (NVH) performance [7].

Hot-stamped tailor welded blanks (TWBs) present a number of opportunities. The industry is experiencing significant changes in design and application for tailored products, and these changes are expected to expand. For instance, a significant number of applications are now mixed material, as opposed to simply dissimilar gauge. With the expanding steel grades, safety and lightweighting engineering teams can tailor sections of nearly every part. The use of TWBs is not the only method for tailoring the strength of a component in localized areas, but tailored tempering processes enables the hot forming of components with precisely defined zones of varying strength or ductility in a single working step. Honda and Gestamp have used such a process to develop a hot-stamped rear frame for the 2016 Honda Civic that weighs 20 percent less the previous Civic [7].

The hot-forming technology employs ultra-high-strength steels, such as 22MnB5. With them, car manufacturers can build lighter, yet stronger and safer vehicles. Press-hardening components made from boron steels requires several processing steps that result in high-strength parts. While the structure of a car body outside the passenger cell is designed to deform and absorb energy, the hot-stamped components used in Body-in-White construction are intended to maintain shape to protect the passengers. Hot forming is mainly divided into two types: direct and indirect hot forming.

Direct Hot Forming: In the direct hot-forming process, the blank is heated in a furnace, transferred to the press and subsequently, formed and quenched in the closed dies as shown in Figure 5.

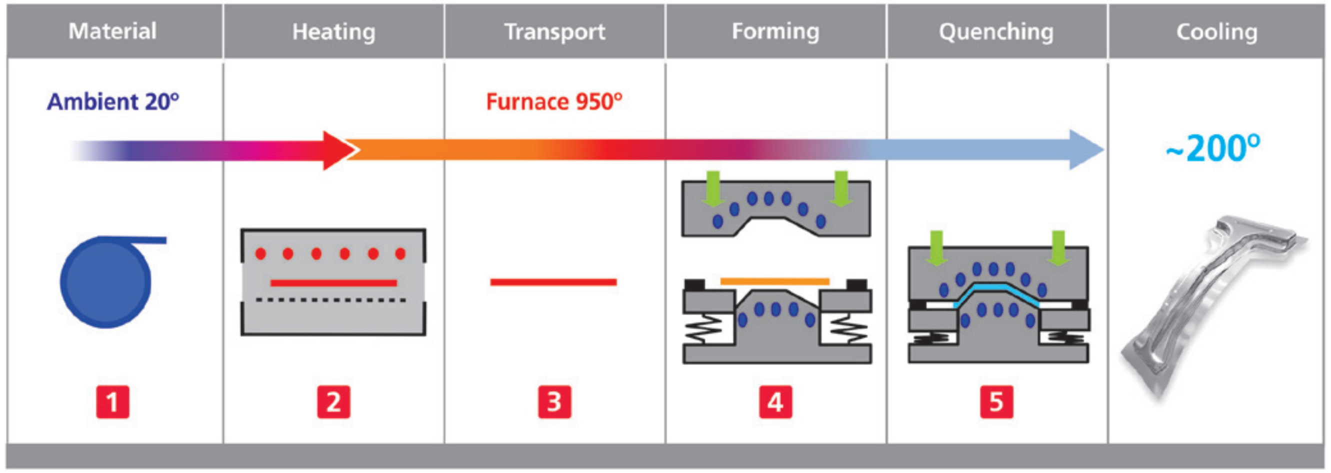

FIGURE [5] / Direct hot forming [8]

The as-received steel is at room temperature (20 to 25 degrees Celsius) with yield strength of 350 to 400 MPa, a tensile strength of 550 to 600 MPa and a total elongation of around 25 percent. To let the material harden, the blank is then heated at around 900 to 950 degrees Celsius to change the microstructure to austenite. This is accomplished in continuous furnaces to ensure a continuous heating process where the blank is heated for 4 to 10 minutes. The exposure of the tool steel to the high temperatures necessary for hot forming can result in large variations in friction as a result of changes in the surface topography, removal of oxide layers and excessive tool wear.

One way to overcome friction issues is to apply suitable coatings or various surface treatments to the tool steel. An aluminum-silicon (AS) coating is the most common one applied to blanks to prevent the formation of this surface oxide. Other coatings include hot-dipped galvanized (GI), galvannealed (GA), zinc-nickel (GP) and organic substances. Inert gases are used for special applications [6]. Then the heated blank is transferred to the water-cooled die by robots or with the help of linear transfer systems (feeders) in about three seconds. To protect the transfer system from overheating and minimize the blank's heat loss, insulation is usually applied. The placement of heat shields between the blanks and the transfer system is a common practice to provide insulation. Once transferred, positioning aids keep the blank precisely located in the die.

Forming temperature typically starts at 850 degrees Celsius and ends at 650 degrees. While in the austenitic range, the true yield stress is relatively constant at 40 MPa with high elongations greater than 50 percent. Higher elongation enables stampings of complex geometries, and lower yield strength reduces springback issues. When forming is completed, the stamping is in contact with the punch and die for both side (through-thickness) quenching. The formed blanks are cooled under pressure for a specific amount of time according to the sheet thickness after drawing depth is reached. During this period, the formed part is quenched in the closed die set that is internally cooled by water circulation at a cooling rate of 50 to 100 degrees Celsius/s. The quench process transforms the austenite to martensite throughout the entire stamping, which accounts for the increase in strength and a greater precision in its final dimensions. The part leaves the hot forming line at approximately 150 to 200 degrees Celsius with a tensile strength of 1400 to 1600 MPa, a yield strength between 1000 to 1200 MPa, and 4 to 8 percent elongations.

Total time for robot transfer, forming and quenching is about 5 to 10 seconds and depends heavily on the quench rate and quenching system. Ultimately, the very high strength and low elongations of the final stamping restrict the secondary operation such as restrike, flanging, crashforming, etc. Therefore, room-temperature stamping should not undergo additional forming. Any special cutting, trimming and piercing equipment must withstand the high loads generated during these operations.

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Indirect Hot Forming: Indirect hot forming was developed to reduce wear on the tool when dealing with uncoated steel and to stamp more complex form features. The indirect hot-forming process is also named as "multi-step" hot forming as shown in Figure 6.

In indirect hot forming, the sheet is uncoiled and cut according to the desired shape in step 1. The blank is then preformed at room temperature by the conventional cold-forming process to approximately 90 to 95 percent of its final shape, shown in step 2. The preformed panel coming out from the cold stamping can be trimmed, flanged or punched in step 3. In step 4, the preformed, semi-finished product is transferred to the continuous furnace and is heated at austenization temperature of 900 to 950 degrees Celsius. Finally, the preformed, semi-finished part is drawn in step 5 to get the final shape of the product and quenched under pressure with the water-cooled tools in step 6. Just like direct hot forming, the quenching operation will transform the austenite to martensite throughout the entire stamping, resulting in higher precision and part consolidation of the final product. Afterward, the product will be trimmed by laser processing or other necessary follow-up processes according to the characteristics of the components or directly output finished product.

BENEFITS OF HOT FORMING

1. In modern hot forming, relatively complex shape parts can be formed at a very high strength in a single step die.
2. Its stress-relieving capability reduces problems with springback and side-wall curl, which is a common problem when cold forming HSS and UHSS.

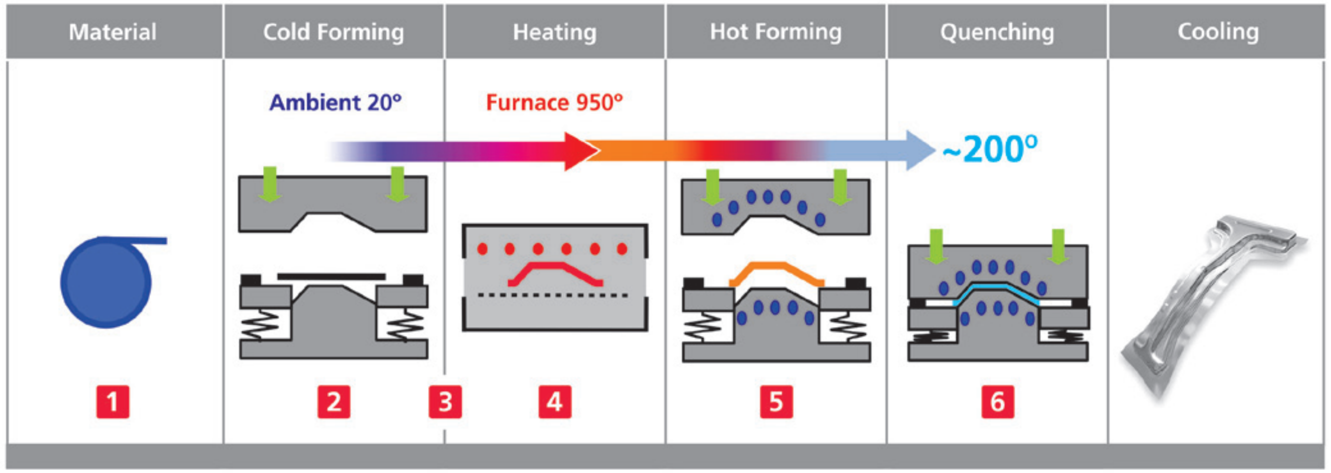

FIGURE [6] / Indirect hot forming [9]

3. Since hot forming allows forming of complex parts in one stroke, multi-component assemblies can be redesigned and formed as one component, eliminating some downstream joining processes such as welding/joining.
4. The tonnage requirement to hot-form a HSS or UHSS part is substantially lower than is needed to cold-form it.
5. Hot-formed parts have both high-yield strength and steep cyclic, stress-strain response, creating excellent fatigue performance.
6. Tailor-welded blanks with different combinations of thickness, properties and surface coatings can be hot formed as a single stamping.
7. Controlling the temperature in various locations of the forming die creates zones with different strength levels in the final stamping.

CHALLENGES IN HOT FORMING TECHNOLOGY

1. The press-hardened parts are too hard to be trimmed using traditional steel-trimming dies, therefore, the final trim must be done with a laser, or the blank has to be optimized to avoid the cutting operation.
2. Multiple processes such as redraw, forming, flanging, etc., cannot be performed because the hot-formed parts are too hard.
3. Press speed of hot forming can reach speeds of 10 to 15 seconds per stroke, making it slower compared to cold forming.

In modern hot forming, relatively complex shape parts can be formed at a very high strength in a single step die.

4. Only boron-based steels (typically 22MnB5) can be hot formed. Galvanized or pre-painted steels cannot be used in this process.
5. Hot forming requires special press and tooling, such as a system to heat the blank, cooling tools to quench the part, automated handling to transfer the hot blank and a part, hydraulic or servo press with dwell capability.

CONCLUSION

Apart from several different advantages, hot forming offers two main benefits for automakers—lightweighting and high-strength, crash-resistant parts. Since hot forming produces lightweight, high-strength parts, it has definitely proved to be one of the effective solutions to the toughest challenges automakers have been facing. You can also create a case for the process' flexibility by making good use of tailored welded blanks, mixing different thicknesses and grades to produce hot-formed parts that show buckling properties (~500 MPa) in some areas and crash-resistant properties (~1500 MPa) in other areas where no deformation under crash is acceptable. This technology certainly can take away some of the burden from OEMs in order to satisfy the emission and safety regulations, and at the same time produce automobiles to meet consumers' expectations.

REAL-LIFE CASE STUDY

Here is a case study of the application of advanced engineering and simulation technology to hot-forming production troubleshooting and process optimization.

Precision Partners Holding Company (PPHC) began its press-hardening journey in 2003 when the tooling division of The Electromac Group partnered with a strategic Tier 1 customer, becoming the exclusive tooling source for their North American hot-stamping operations. Although Electromac Tool had long been established as a leader in the design and build of complex stamping dies (with a niche in Class-A bumper tooling), we embraced the opportunity to broaden our areas of expertise and plunged headlong into this expanding new technology. After several years of building hot-stamping tools for Tier 1s in North America and Asia, in 2011, PPHC expanded the manufacturing side of the company (Cannon Automotive Solutions) to include the production of press-hardened components.

Due to the inherent challenges of press-hardening, accurate finite element analysis (FEA), the proper interpretation of these simulations is critical to ensure product manufacturability and process optimization. What follows is a case study that demonstrates this best.

Failure Analysis/Resolution

PPHC, based on their acknowledged tooling expertise, was called in by an OEM customer to troubleshoot, diagnose and resolve panel splitting on a hot-formed production line. Fluctuations observed in production conditions were leading to localized splitting in more than 30 percent of produced parts, shown in Figure 7.

We began by importing the tool faces supplied by the original die source into the AutoForm software to simulate the current tooling process. Analysis of these simulation results confirmed that thinning in the problematic area shown in Figure 8 was, indeed, exceeding the upper limit of what are we considered the threshold for a maximum thinning percentage.

Since this vehicle was fully launched, there was very limited opportunity for product concessions. Taking into consideration the adjacent parts in the vehicle assembly, as well as the current spot-weld locations, we made several iterations of form modifications to the product design until the AutoForm results were within our pre-determined "safe-zone" for maximum thinning, as shown in Figure 9.

FIGURE [7] / Splits in original part geometry

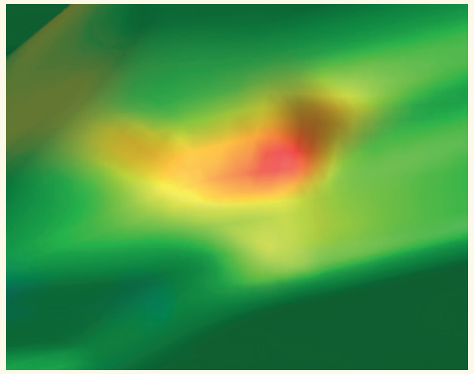

FIGURE [8] / Correlated AutoForm results (~19% localized thinning)

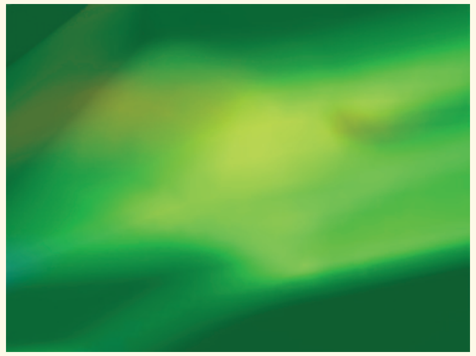

FIGURE [9] / Thinning results after form modification (~11% maximum thinning)

FIGURE [10] / Thinning correlation

These geometry alterations entailed targeted removal of punch material until localized strain was reduced and dispersed. Our AutoForm results and the modified part data were passed upstream to the OEM. Since none of the adjacent assembly had been modified, the weld layout remained unchanged, and the part had not lost rigidity or strength, approval to make the change was expedited. The dies arrived at PPHC on a Friday, and over the course of a weekend, our tooling division welded the form sections, and CNC cut them to match the simulation-developed geometry. The dies were re-spotted, and trial runs exhibited no tendency for weakness or splitting, as shown in Figure 10.

Cross-sectional, pin-micrometer checks showed the correlation between predicted thin-out from AutoForm and actual readings to be within half a percentage point. The tools returned to the stamping plant on the Monday morning, and the fallout due to splitting was eliminated. LW

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Norm Lehn is the PHS & FEA engineering lead at The Electromac Group, developing complex tooling and component assemblies for both the hot and cold stamping segments. Mr. Lehn started working with The Electromac Group in 1991 and has more than 15 years of experience in PHS engineering, tool design and press hardening line integration. In addition to his 10 years of FEA experience specializing in press hardened components and complex geometries, Mr. Lehn an R&D tech leader focusing on lightweighting is developments.