

Evaluating Hot Forming in Automotive Manufacturing and Its Transferability to Other Industries

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Abstract

Auto manufacturers must build vehicles that are lighter and safer at the same time. Hot forming meets that demand by heating a boron-steel blank, forming it, and quenching it in one die, so that ordinary sheet leaves the press as ultra-high-strength steel. This review evaluates hot forming in automotive manufacturing and asks which of its lessons transfer to other industries such as aerospace, construction, wind turbines, and railroad transportation. It finds that the process earns its place where a part needs a complex geometry, different crash behaviour in different regions, and volumes large enough to repay the line. That strength is bought with heat: on a modelled production line, the furnace drew 77.51% of total energy. The sustainability case is therefore conditional, holding only where a vehicle's use phase repays the furnace through fuel saved by lighter mass. Aerospace shares part of this case, while construction and wind turbines do not, leaving material savings as their only argument.

1. Introduction

Every manufacturing industry asks something different of its structural parts. Whether the goal is low weight, rigidity, or safety, each industry must choose a material, a temperature, a tool, and a trade-off. In automotive manufacturing, that choice is shaped by two demands that pull against each other: vehicles must become lighter and safer at the same time (Taylor and Clough 809). Shedding mass must not weaken the parts responsible for protecting occupants in a collision. For those crash structures, the automotive answer is hot forming, a process that runs on furnace heat and hardens steel inside the very tool that shapes it.

Hot forming, also called hot stamping or press hardening, heats a boron-steel blank to about 900–950 °C, transfers it to a press, and forms and quenches it in one water-cooled tool, so that a sheet delivered at roughly 600 MPa leaves the die at roughly 1,500 MPa (Karbasian and Tekkaya 2103). The literature on the process comes from two perspectives that agree on this core transformation and differ in what they measure. The metallurgical literature treats hot forming as a coupled problem in heat transfer, deformation, and phase change, and asks how accurately it can be modelled (Karbasian and Tekkaya 2108). The industrial literature treats it as a manufacturing decision and asks what it costs, what it replaces, and how quickly carmakers have adopted it (Taylor and Clough 809–11). A third, newer body of work measures the energy and life-cycle consequences of the choice (Gonçalves et al. 339). This review draws on all of them and writes for the student reader who wants to understand manufacturing decisions.

Hot forming delivers several advantages at once: strength, crash performance through tailored properties, geometric control with minimal springback, and part consolidation (Karbasian and Tekkaya 2103, 2113, 2116; Taylor and Clough 820–21). These gains are bought with heat. The furnace at the centre of the process dominates the line's energy demand, drawing more than every other piece of equipment combined (Liu et al. 1). A lighter vehicle burns less fuel

over its life, but making it can cost more energy up front, so the net benefit holds only when the use phase repays that production cost (Kim and Wallington 6089). The environmental case for hot forming is therefore legitimate but not without trade-offs.

Within automotive manufacturing, hot forming offers compelling advantages over competing processes, and related temperature-controlled forming methods exist in aerospace (Sana 1), railroads (Yi et al. 1), and other sectors. For an early-career engineer or a student encountering the field, there is no single accessible summary that evaluates the automotive case across its full set of trade-offs and then asks which of those lessons apply elsewhere. This review aims to fill that gap, written for readers new to the field.

Hot forming has become automotive's method of choice for ultra-high-strength structural parts because it meets several demands at once: strength, crash performance, complex geometry, part consolidation. Achieving more than one of these demands depends on conditions particular to automotive and a use phase in which the part is in motion. Section 2 describes the hot forming process and its metallurgy, Section 3 sets out the engineering reasons for it, Section 4 measures what it costs, and Section 5 weighs its sustainability report card. Section 6 evaluates those conditions in four industries beyond automotive.

2. Background: What Hot Forming Is and Why It Works

Hot forming, also known as hot stamping or press hardening, is a process used to turn conventional steel into ultra-high-strength steel (UHSS) through a sequence of heating and cooling events. First, a metal coil is mounted onto a decoiler and unwound as a strip. The strip passes through a straightener, which ensures a flat sheet. A servo feeder advances the sheet into the blanking press, synchronised with the press stroke, where the blanking die shears the metal at set intervals to produce the flat starting piece, known as a blank. A conveyor then carries the blanks to the furnace storage unit, where a robot places each blank in the furnace. The blank is heated to 900–950 °C until its room-temperature structure converts into austenite, and a second robot transfers the hot blank to the die, where it is formed and quenched by water-cooled tooling.

This review describes the direct method, in which the flat blank is heated before any forming takes place; in the indirect method, the blank is cold pre-formed first, and the press performs only final calibration and quenching (Wróbel et al. 2). Across that sequence, tensile strength rises from roughly 600 MPa in the delivered sheet to roughly 1,500 MPa in the finished part (Karbasian and Tekkaya 2103). Two conditions decide whether the increase occurs. The blank cools by 100–200 °C on its way from furnace to press, and if it falls below the temperature at which ferrite begins to form, only part of the section will harden (Taylor and Clough 818). It must then be cooled in the die faster than about 27 K/s (Karbasian and Tekkaya 2104). Heat transfer, deformation, and microstructural transformation occur together, and each alters the conditions of the others, so the sequence cannot be understood one stage at a time (Karbasian and Tekkaya 2108).

The steel in question is almost always 22MnB5, the most common boron-manganese grade used in hot forming, and its name gives most of its composition. The number “22” refers approximately to a carbon content of 0.22%, while “Mn” and “B” indicate manganese and boron.

The exact composition varies slightly between steel manufacturers and customer specifications; a commercial 22MnB5 measured for hot press forming contained 0.220–0.250% carbon, 1.200–1.400% manganese, and 0.002–0.005% boron (Chang et al. 60).

Hot forming is effective because steel does not have one permanent internal structure. Its atoms can rearrange into different crystal structures depending on temperature, chemical composition, and cooling history. These arrangements are called microstructures, and each has different mechanical properties. As delivered, 22MnB5 is ferrite, whose body-centred cubic lattice holds little carbon, mixed with pearlite, a layered structure of ferrite and iron carbide. Heating above roughly 830 °C converts both into austenite, whose face-centred cubic lattice dissolves the freed carbon and deforms readily, which is why the blank is shaped hot rather than cold (Taylor and Clough 817, 819). The cooling rate determines the final microstructural form. Below the critical rate, carbon diffuses far enough for ferrite, pearlite, or bainite to reform; above it, the iron lattice shifts before diffusion can occur, and the retained carbon stretches the structure into a body-centred tetragonal form (Karbasian and Tekkaya 2107). Martensite is that strained condition, and the strain rather than the atoms themselves is what resists deformation. Although carbon determines the martensite's hardness, too much carbon costs the ductility and weldability the finished part still needs (Taylor and Clough 814; Wróbel et al. 5); manganese and boron instead raise hardenability, with boron delaying ferrite formation enough to make a die-quench rate as modest as 27 K/s sufficient (Karbasian and Tekkaya 2104). A die-quenched part is more than 95% martensite (Chang et al. 61).

3. Evaluation I: What Hot Forming Delivers

Hot forming entered the automotive industry because it decoupled the traditional inverse relationship between exceptional material strength and geometric formability, resolving a structural dilemma for car manufacturers in the late twentieth and early twenty-first centuries. Body structures had to become lighter while meeting increasingly strict crash standards, and because the density of steel is essentially fixed, a lighter steel part can only come from a thinner sheet (Taylor and Clough 809). Thinner sheet, however, gives up strength, stiffness, and formability, and it springs back further after cold stamping (Taylor and Clough 809–10). Hot forming escapes that bind by shaping the blank while it is soft and hardening it only once the geometry is fixed: 22MnB5 enters the furnace at about 600 MPa and leaves the die at about 1,500 MPa (Karbasian and Tekkaya 2103), with some hot-stamped parts reaching 2,000 MPa (Wróbel et al. 2). The formability of the hot blank permits complex geometry and a thinner gauge without sacrificing resistance to intrusion (Taylor and Clough 819, 823).

Crash safety in a hot-formed part is a design outcome rather than a trade-off against strength. A fully martensitic region reaches up to 1,500 MPa but only about 5% elongation (Karbasian and Tekkaya 2115–16), which suits a region that must resist intrusion into the passenger space but not one that must deform and absorb impact energy. Hot forming lets the designer decide where each behaviour happens: a B-pillar can control intrusion in its upper section while absorbing energy in its lower one (Karbasian and Tekkaya 2116). The softer region can be produced by holding part of the blank below full austenitization in the furnace (Taylor and Clough 851), by heating segments of the die so that martensite cannot form against them (Wróbel et al. 8), by tempering selected areas after stamping (Wróbel et al. 8), or by joining

different steels into one blank before forming (Taylor and Clough 849). A soft zone is softer and more ductile than the fully martensitic region, so it can deform more in a crash; steels developed for energy-absorbing areas target 450–600 MPa with more than 15% elongation (Wróbel et al. 7). Table 1 compares tensile strength before and after each route. Tailored heating, partial die quenching and tailor-welded blanks show that hot forming is no longer only a method for producing one uniformly hard component. It can also be used to engineer how different sections of a single part behave during a collision.

Table 1*Strength and Hardness of 22MnB5 Steel Before and After Tailored Heat Treatment*

Route	Before (as delivered)	After: hard zone	After: soft zone	Soft-zone microstructure	Source
None (baseline)	≈ 600 MPa	≈ 1,500 MPa	Not applicable	Martensite throughout	Karbasian and Tekkaya 2103; Taylor and Clough 815–17
Tailored heating	≈ 600 MPa	≈ 450 HV	≈ 280–300 HV	Ferrite + martensite	Karbasian and Tekkaya 2115 (hardness); Taylor and Clough 851 (microstructure)
Tailored quenching	≈ 600 MPa	Not reported	Not reported	Tempered martensite, bainite, or ferrite	Taylor and Clough 851

Note. Values are reported as each source gives them; hardness (HV) and tensile strength (MPa) are related but not interchangeable, so rows are compared within a unit rather than across units.

Hot forming's geometric advantage is less about any single shape than about how many parts a structure needs. Because the blank is formed soft, complex geometries become possible, giving designers the freedom to tune stiffness and position crash folding triggers and weld access points within one component (Taylor and Clough 819). That freedom allows consolidation, which shortens process time and lowers cost because there are fewer pieces to stamp and join (Taylor and Clough 820). The tunnel assembly of the 2012 Škoda Rapid shows the scale of the change: a cold-stamped design of seven parts and 115 welding points became two hot-stamped parts with 14 welding points, weighing 9.5 kg instead of 13.55 kg and costing 30% less to manufacture (Taylor and Clough 820–21). The consolidated design is also stiffer, since the heat of welding leaves joints either softened or embrittled relative to the parent steel (Taylor and Clough 821). Material efficiency starts at blanking, where sheet width is matched to the longest dimension of the blank to minimise scrap (Taylor and Clough 817). These shapes also hold their dimensions: hardening inside the closed die leaves hot-stamped parts with minimal springback (Karbasian and Tekkaya 2113), sparing the corrective post-processing that cold-stamped high-strength parts often require (Taylor and Clough 822). This review infers that fewer parts, fewer welds, and less scrap also reduce manufacturing energy and material waste, independent of how the finished part performs in service.

Worldwide production of hot-stamped boron steel parts rose from 9 million in 1997 to 107 million in 2007 (Taylor and Clough 811). Within a single model line, hot-stamped sheet steel grew from 7% of the body-in-white of the 2003 Volvo XC90 (Taylor and Clough 829) to 38% of

the 2014 model, saving 22 kg against its predecessor (Taylor and Clough 830). Hot stamping now produces 15–38% of the weight of car-body drawpieces, a share expected to keep growing (Wróbel et al. 1–2), and the field's research agenda includes shorter cycle times and scaling up new heating methods (Taylor and Clough 856–57). The automotive industry is committed to hot forming for strength, safety, geometry, and assembly.

4. Evaluation II: What It Costs

Hot forming delivers what other forming processes cannot: a fully martensitic part. The microstructure is worth having, but the route to it is demanding. Hot stamping consumes more energy than cold stamping precisely because the blank must first be heated (Gao et al. 11). Martensite forms when the hot blank is quenched between cooled dies, yet the press is not where most of the energy is consumed. That happens earlier, in the furnace, where the blank is heated and held until it is fully austenite (Liu et al. 5). On a modelled roller-hearth line, the furnace drew a measured 521.68 kWh over an hour of operation, 77.51% of the line's total, while the press accounted for 10.92%, the chillers 6.86%, the cooling system 2.76%, and the robots 1.95%. Per kilogram, the same line is modelled at 0.597 kWh and measured at 0.625 kWh (Liu et al. 1, 21).

Heat escapes the furnace by three routes: through the outer walls, through doors held open as blanks are loaded, and with the protective atmosphere as it is exhausted (Liu et al. 8). Only the first is a construction problem, addressed with layered walls that combine a refractory lining, an insulating layer, and an outer enclosure (Liu et al. 8). The arithmetic is instructive: removing the press and chillers entirely would not cut the line's energy by a fifth, whereas halving the furnace's demand would save almost two-fifths (this review's calculation from the shares in Liu et al.). The furnace on this line is electric, but roller-hearth furnaces may also burn gas or combine both (Liu et al. 6).

Across a modelled hot-forming chain, one that quenches the part in a tank rather than in a die, producing the raw material accounts for 88.27% of a part's CO₂, and heating is a distant second at 10.68% (Ghattamaneni et al. 2347–48). Once material is set aside, heating makes up about 91% of what remains, which is why recovering heat is the next lever after saving material (Ghattamaneni et al. 2348). The proposed concept is modest: warmth from parts leaving a 400 °C tempering step would preheat incoming blanks, yet it reaches the required 150 °C only with channels at least 21 m long (Ghattamaneni et al. 2348, 2352). The chain is modelled rather than measured, so its shares are estimates (Ghattamaneni et al. 2353). Cost alone cannot settle whether hot forming is worth it; the answer depends on what the finished part does after it leaves the press.

5. Evaluation III: The Sustainability Angle

Hot forming earns its sustainability claim in industries where the formed part spends its life in motion. A lighter vehicle requires less energy to accelerate and to hold at speed, burns less fuel to do so, and emits less CO₂ for every kilometre it travels; the mass removed at the press is therefore converted into avoided emissions continuously, for as long as the vehicle remains in service. For a conventional internal combustion vehicle, roughly 0.0012–0.0015 L of

fuel per 100 km is saved for each kilogram of curb mass removed, so a 100 kg reduction returns over 300 L of fuel across a 150,000 km use phase, and adapting the powertrain to restore the original performance can multiply that saving by a further factor of three or four (Koffler and Rohde-Brandenburger, qtd. in Raugei et al. 80). Because the saving accrues over the whole service life, it repays the furnace. The use phase accounts for 63–92% of total vehicle life-cycle energy consumption, against 8–32% for materials production and only 1–4% for manufacturing and assembly (Kim and Wallington 6090), with a later review placing the use-stage share at 84–91% (Gonçalves et al. 339). All thirty-three studies harmonised in that analysis show that replacing conventional steel with a lightweight alternative, whether aluminium, glass-fibre reinforced plastic or high-strength steel, reduces life-cycle energy use and greenhouse gas emissions (Kim and Wallington 6089), and across twelve cradle-to-grave studies of chassis and body-in-white components, advanced and high-strength steels emerge as the most preferable lightweight material, ahead of aluminium, on the strength of a less energy-intensive production route and end-of-life recycling rates of 80–95% (Gonçalves et al. 342–43). The furnace is paid for, but only by an operational phase in which mass costs energy.

That repayment is conditional rather than universal, and the condition is that the part spends its life in motion. The argument holds only where saved weight is continuously converted into saved fuel; where there is no moving use phase, it cannot be made. Construction is the cleanest illustration. Used in the foundation or frame of a building, the same ultra-high-strength steel still yields a lighter member, but the lightness buys nothing operationally, because no energy is spent moving the structure from place to place (this review's analysis). There is no mass-dependent use phase to compensate for the furnace. Whatever sustainability case exists for hot forming in such a sector must be won entirely at the point of production.

Such a case can be won, and a study that switches the use phase off has already demonstrated it. A cradle-to-gate assessment found total emissions of 11 kg CO₂e per demonstrator part for hot stamping against 17 kg for cold stamping, a difference of 6 kg attributed primarily to material savings, since the hot-formed part required 400 g of sheet against 670 g for equivalent structure and strength (Bucconi et al. 270). A cradle-to-grave assessment of a 31 kg floorpan reaches a similar conclusion by a different route, finding the additional process energy was more than compensated for by improved end-of-life recyclability, with maximum reductions of 20% for global warming potential and 46% for human toxicity potential, but only under fully closed-loop recycling (Raugei et al. 83, 85). Both studies used aluminium alloys rather than 22MnB5, and both inform the steel case by analogy only.

Hot forming is the right answer to a particular combination of demands, and three conditions have to coincide for it to be one. The part must need a geometry too complex to hold at ultra-high strength, which forming soft and hardening under constraint delivers (Taylor and Clough 819; Karbasian and Tekkaya 2113). It must survive an impact, since tailored properties are worth engineering only where one component has to resist intrusion in one region and absorb energy in another (Karbasian and Tekkaya 2116), and it must be made in volumes large enough to return the investment in the line (Taylor and Clough 853). Where all three exist, as in a B-pillar or a tunnel assembly, consolidation, reduced scrap, and use-phase mass savings justify the cost of heating (Taylor and Clough 820–21). Where one is missing, another way of forming metal may be the better choice. Those three conditions are also what to look for in any other industry.

6. Lessons for Other Industries

Outside automotive, the same problem is solved by processes that share hot forming's principle, but not its name, material, or metallurgy: superplastic and isothermal hot forming for titanium (Wang et al. 2), creep-age forming for aluminium panels (Zhan et al. 1), and hot form quench for aluminium skins (Yi et al. 1). Even aerospace "hot forming" holds tool and blank at one temperature and forms over minutes, unlike the seconds-long die quench of press hardening (Sana 5).

Aerospace comes closest. Aircraft also share the automotive use phase, and lighter airframes are one way the industry has reduced operational energy (Khan et al. 1). Titanium alloys in nacelles, pylons, and engines have complex geometries that are difficult to shape using cold processes, so the sheet is formed at 650–950 °C by superplastic forming or by isothermal hot forming (Sana 1–3). Excluding manufacturing, a 1 kg titanium part saves about 11,300 MJ in lifetime operational energy compared to an equally stiff aluminium part (Khan et al. 5–6, 10). Like the automotive industry, manufacturing decisions for aerospace are made partly at production. Material efficiency is the clearest shared lesson: hot-formed titanium parts hold a uniform thickness that lets the starting blank be optimised, which saves raw material (Sana 6). An aerospace hot-forming press produces about 3,100 parts a year on three shifts over 240 days (Sana 8), while an automotive hot-stamping line running at 188 stampings an hour (Liu et al. 15) would produce over a million parts on the same schedule, by this review's calculation, making production output lower in aerospace.

Railroad vehicles have a use phase in motion, but the lightweighting payoff is already collected by aluminium, whose car bodies weigh 30–50% less than steel ones (Sun et al. 2). The resemblance to automotive is geometric. One high-speed train's front is shaped mostly by hammer press in about 70 panels joined by roughly 170 m of weld (Sun et al. 10), and a 5083 aluminium skin formed hot at 450 °C met its thickness and springback limits (Yi et al. 1, 9). Its yield strength rose only 18.5%, through work hardening rather than a phase change, because 5xxx alloys cannot be strengthened by heat treatment (Yi et al. 1, 11). Whether press-hardened boron steel could replace aluminium panels on cost is untested in the sources reviewed here, and aluminium's lower density and stronger corrosion resistance suggest boron steel would struggle to displace it (Sun et al. 1–2; this review's speculation).

Construction and wind turbines have no use phase in which reduced mass saves energy, so the only sustainability argument left for hot forming in these sectors is the one Section 5 found with the use phase switched off: using less material. Wind turbines mounted on taller towers require more steel vs. shorter towers. Comparing the life cycle assessments for different tower types (conventional vs. hybrid, tall vs. short) is useful for understanding the carbon emissions involved with manufacturing each type (Gkantou et al. 15). The reported tower types used cold-formed S355 hollow sections rather than hot-formed ones (Gkantou et al. 7). Future innovations in manufacturing through hot forming may reduce the material needed and the carbon emissions associated with making the towers.

Set against the three conditions from Section 5, none of the four sectors meets all of them. Aerospace meets the geometric condition most clearly, since superplastic forming produces very complex titanium shapes free of springback (Sana 5). It falls short on the other

two: its hot-formed parts serve in hot, corrosive zones such as nacelles and engines rather than in crash structures (Sana 1), and even an automated press cell reaches just over 7,000 parts a year (Sana 8). Railroads share the geometric condition, but 5xxx aluminium cannot harden through a phase change, so the tailored crash zones of Section 3 are unavailable (Yi et al. 11), and no source reviewed here reports railroads' crash requirements or production volumes. Construction and wind turbines meet none of the three, as their towers rely on simple cold-formed sections and carry no crash load (Gkantou et al. 7). For both sectors, the open question is whether hot forming could save enough steel to repay its furnace, and the forming literature cannot yet answer it. Models of single lines and process chains exist, as Section 4 shows, but as of 2011 no general model compared the environmental burden of one forming route against another (Ingarao et al. 345–46). The study that would settle the question would compare a tower member hot-formed at equal structural performance against the cold-formed section it replaces, weighing the furnace energy against the steel saved.

7. Conclusion

Hot forming is especially useful for industries whose life-cycle assessments favour the use phase, but only where three conditions meet: a complex geometry, a part that must resist intrusion in one region and absorb energy in another, and in output volumes large enough to repay the energy costs for operating the entire manufacturing line. The automotive industry meets all three, and because its vehicles run on fuel, the use phase compensates for the energy spent on lightweighting. This is also why hot forming is regarded as sustainable. However, for industries such as construction and wind turbines, the argument does not hold, because their products do not move and they meet none of the three conditions. Aerospace presents a stronger opportunity for wide application compared to construction and wind turbines; it shares the geometry factor and a use phase in which even relatively small reductions in aircraft mass can translate into significant reductions in fuel consumption and emissions over thousands of flight cycles, though it falls short on crash duty and volume. The automotive industry's widespread adoption of hot forming demonstrates the value of this manufacturing process. Such achievements through hot forming may incentivize industries with clear use phases to explore their own adaptations.

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