

Chapter 7

Post-Forming Operations



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Abstract Once an automotive part is formed and quenched, it may be required to trimmed/pierced, shot blasted (depending on the coating) and then welded to subassemblies and assemblies. It is essential to understand all these steps of manufacturing. After each and every step, quality control—both online and offline—has to be done. This chapter discusses the so-called “Post-Forming Operations”.

7.1 Typical Process Chain

Hot-stamping process starts with a coil of sheet steel and ends with the final component or the subassembly. The first process in the chain is decoiling and blanking. The blanks are stacked and moved to the furnace loading area. Another material handling unit takes one batch at a time—which may be up to four blanks per batch—and places them into a furnace. The furnace heats the blanks over their austenitizing temperature. The blanks are then transferred quickly to a press where forming and quenching are done consecutively. The parts are moved out of the press and typically laser trimming/piercing is the last process before welding the component to a subassembly. A typical process chain is shown in Fig. 7.1 [1].

A summary of process chain depending on different blank coatings and process types are shown in Fig. 7.2.

This chapter discusses only the post-forming operations.

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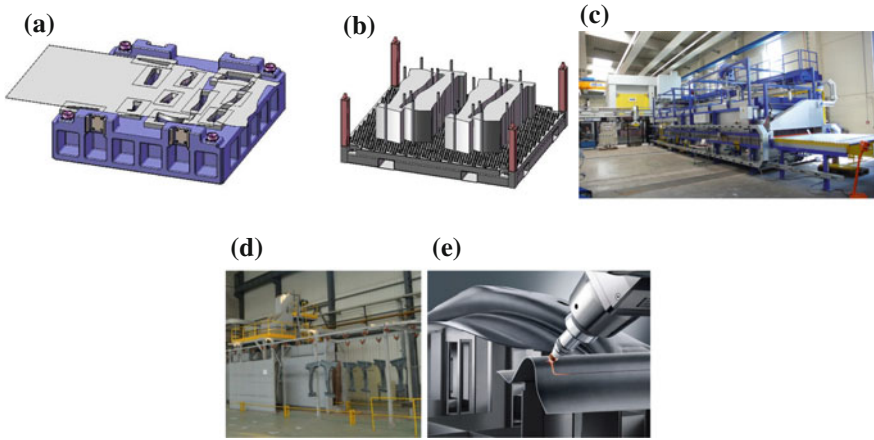


Fig. 7.1 Typical process chain for a hot-stamped component: **a** blanking, **b** material handling, **c** heating, forming and quenching, **d** surface conditioning, **e** trimming/piercing [1–4] (The last two are not mandatory, and depending on the process they may not be required)

Blank coating	Uncoated		AlSi	x-tec	Zn-coated (GI or GA)	
Process type	Direct	Direct	Direct	Hybrid	Indirect	Multi-step
Pre-Processes	Blanking					
				Cold pre forming	Cold pre forming and trimming	
Heating	Heating in the furnace					
		Controlled atmosphere		Controlled atmosphere	Controlled atmosphere	
Forming / Quenching	Forming and quenching in a cooled die				Only quenching in a cooled die	Forming and trimming in servo transfer press
	Shot blasting			Shot blasting		
Post-processes	Laser trimming					

Fig. 7.2 Summary of the process chains with respect to blank coating and process types (re-created after [5, 6])

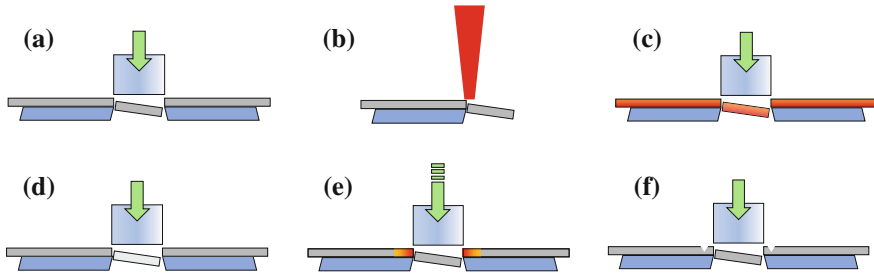


Fig. 7.3 Cutting (trimming, piercing) methods for hot stamped components: **a** hard cutting, **b** laser cutting, **c** hot cutting, **d** cutting of soft zones, **e** adiabatic cutting, **f** cutting with notches [re-created after [7–10]]

7.2 Trimming and Piercing

After hot stamping, the parts may be required to cut. If a hole or shape is cut inside the blank, this is called “piercing”. If the periphery of the part is cut, this is called “trimming”. In indirect and multi-step hot-stamping processes, post-form trim/pierce are not required. Thus, trimming and piercing are part of direct hot stamping process chain (typically applies to AlSi-coated or uncoated blanks).

Since hot-formed parts have a tensile strength of 1500 MPa (~220 ksi), press forces and tool stresses are extremely high in conventional hard cutting. Thus, several trimming/piercing methods are developed for hot stamping, as shown in Fig. 7.3.

7.2.1 Hard Cutting

Due to very high tensile strength, press forces, and tool stresses are extremely high, in the order of a few hundred tons and 2700 MPa, respectively; if hard trimming would be used (Fig. 7.3a) [11]. Faster wear of the trimming dies and high maintenance cost of the trimming press are still a problem [12].

Laumann [11] studied the effect of hardness on the failure of trimming dies. As seen in Fig. 7.4a, uncoated tool steels would wear out if they were not hardened. Toughness of most tool steels would be reduced as their hardness is increased. Thus, a harder tool steel which would have more wear resistance would now fail by chipping and fracture (Fig. 7.4a). These results show, if hard trimming/piercing would be done, special powder metallurgy tool steels and/or advanced tool coatings would be required [11, 13]. According to a steelmaker, one of the most common tool steels AISI D2 (also known as 1.2379) would fail almost immediately in trimming of 1.6 mm thick, hardened 22MnB5 [14].

Several tool steels and treatments (i.e., nitriding, coating, etc.) are proposed to improve the tool life of hard cutting. One study showed that in piercing holes in a B-pillar, AlCrN PVD (Physical Vapor Deposition) coating would improve the tool

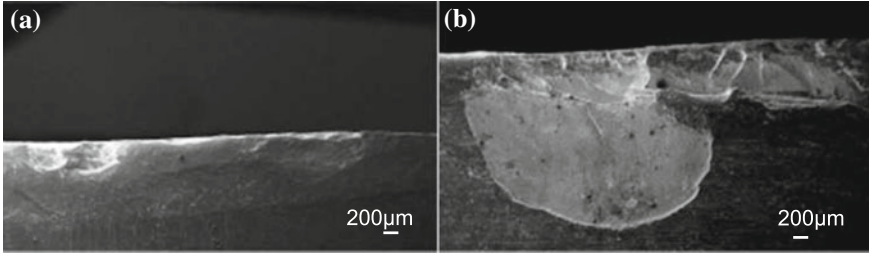


Fig. 7.4 Damage in the cutting edge after 5000 trimmings: **a** areas with low hardness (~ 59 HRC) wears out, **b** whereas high hardness (~ 63 HRC) areas failed by chipping/fracture [re-created after [11]]

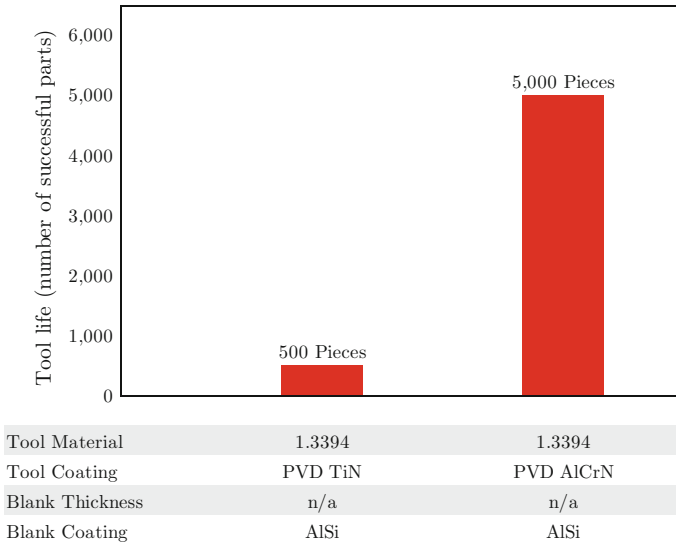
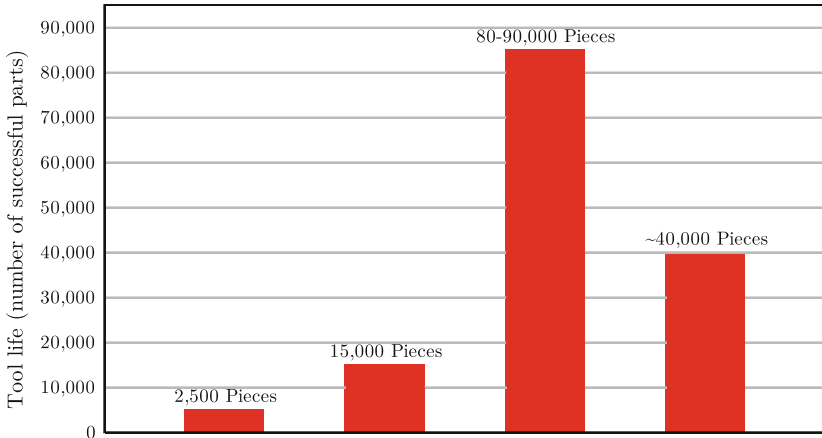


Fig. 7.5 Tool life of TiN-and AlCrN-coated dies, for piercing AlSi-coated 22MnB5 [re-created after [13]]

lifetime by tenfold, Fig. 7.5. Although the overall tool life was still low (5,000 pieces); both tool wear and burr formations were reduced [13] (Fig. 7.6).

As early as 2002, Industeel developed a new tool steel in X110 CrMoV8 family, trademarked as Tenasteel® [15]. In a study in 2011, Tenasteel was used to trim hardened 22MnB5 B-pillars, the tool life was found to be in the order of $\sim 80,000$ for 1.6 mm thick material, and dropped to $\sim 40,000$ for 1.8 mm thick material. The same study also confirmed that the typical tool steel D2 (1.2379) could not trim 1.6 mm thick blanks [14]. Another study in 2015 showed that trimming life could be improved with hard coatings [16]. It has to be noted that for a typical hot stamping line, daily production could be calculated as the working hours divided by cycle time



Tool Material	P/M Steel	P/M Steel	Tenasteel	Tenasteel
Tool Coating	Uncoated	BN Coated	Uncoated	BN Coated
Blank Thickness	2.2 mm	2.2 mm	1.6 mm	1.8 mm
Blank Coating	AlSi	AlSi	AlSi	AlSi

Fig. 7.6 Trimming tool lives under different conditions (re-created after [14, 16])

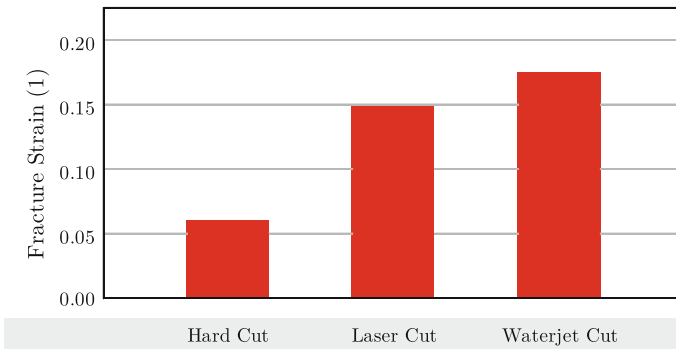


Fig. 7.7 Fracture strain of 22MnB5 after hardening and cutting, measured by DIC method (re-created after [18])

and overall equipment efficiency (OEE). In a 3-shifts plant, 6,000 parts could be manufactured in 20 s cycle time and 70% OEE.

Hard cutting creates burrs, shear zone, and a fracture zone which may have micro-cracks and other irregularities [17]. These irregularities reduce the fracture strain, which would affect the crashworthiness of a component, as seen in Fig. 7.7. In this study, tensile specimens were produced with different cutting methods and the fracture strains were measured via Digital Image Correlation methods [18]. Another study in Spain has shown that the cut edge quality had a direct effect on the fatigue strength as well, Fig. 7.8 [19].

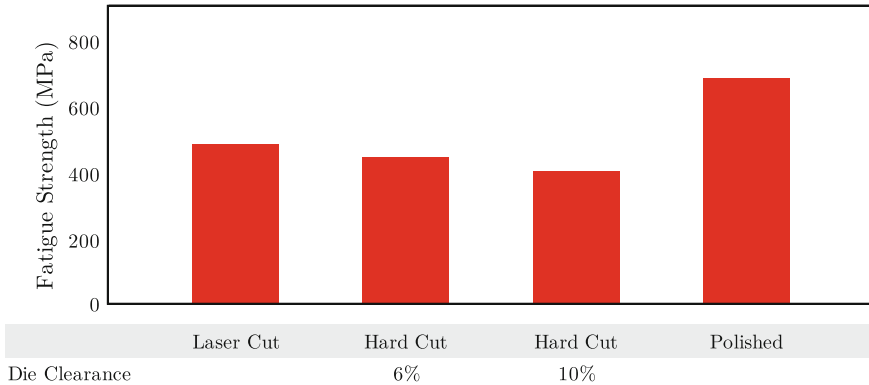


Fig. 7.8 Fatigue Strength after hardening and cutting (re-created after [19])

Several modifications to hard cutting are also proposed, these are discussed in Sect. 7.2.3.

7.2.2 Laser Cutting

Currently, laser cutting is the most commonly used method for cutting purposes. The advantage of using the laser is, that there is no limitation on the shape of the parts to be trimmed. The disadvantages are relatively long cycle times and high capital investment and maintenance cost [19, 20]. However, as explained in the previous section, laser cut parts may have higher fatigue strength and failure strains. The latter one is a significant contributor to the crashworthiness [18, 19].

In principle, when laser is absorbed by a surface, the surface is heated by radiation. When excessive heat is focused on a very small area (i.e., high power density), laser can be used for cutting purposes. Depending on the material type and thickness, cutting could be achieved by evaporation or melting. In the case of hot stamped steel, laser melts the material in the kerf (the width of the cutting groove). Molten steel is removed by reactive gas [21].

Laser cutting can be easily automated. Laser cutters have been long available for fabrication of 2D blanks [21]. Laser blanking (i.e., preparing the initial blanks for hot-stamping process, see Fig. 7.1a) is also proposed and used for small batch production; a hot stamper would use laser cutting to trim/pierce the hot-formed part [20, 22]. Thus, for hot-stamping industry, laser cutters are either 5-axis machines or robotic [2]. Typical five-axis machines have rotary tables with two-parts fixtures. While one fixture is rotated inside the laser cutting machine, an operator can unload the trimmed part from the previous cycle and load the untrimmed part for the next cycle [23]. The time for rotation could be in the order of 2–2.5 s, whereas the dead time between two cycles is as low as 5 s [7].

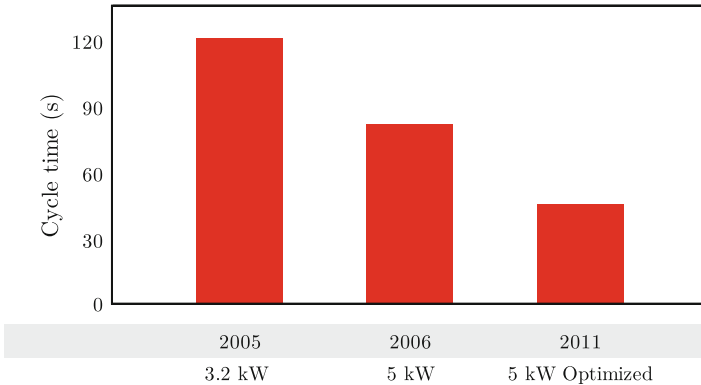
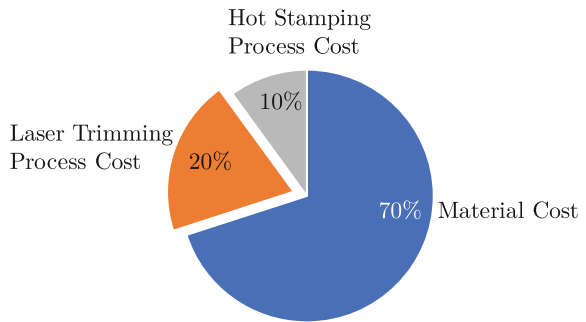


Fig. 7.9 Cycle time improvement in laser cutting of a B-pillar, cutting length is 6.3 m, (re-created after [24])

Fig. 7.10 Approximate cost breakdown of the most common process: direct hot stamping of AlSi-coated 22MnB5 followed by laser trimming (re-created after [22])

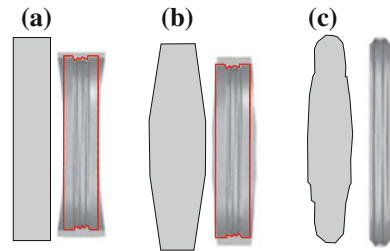


When Volkswagen started with Passat production in 2005, the part required a total of 6.3 m (~20.7 ft) cutting length: periphery trimming and 22 piercings. At that time, a 3.2 kW, five-axis laser machine was used for the job, and the total cycle time was 120 s. Through several optimizations, the cycle time is reduced to ~45 s levels in the next few years, Fig. 7.9. Now with the very low cycle times, an operator may not be fast enough to unload/load parts. Thus robotic loaders/unloaders are becoming more common [24]. One has to notice that nowadays 45 s cycle times are standard for laser cutting, however, the hot-stamping press cycle is around 15 s, and in one cycle two or four parts are typically hot stamped. Thus, per each hot-stamping press, three to six laser cutters may be required [23, 25].

Laser cutting can achieve ± 0.5 mm tolerances in hot-stamped automotive components [26]. For the areas with larger acceptable tolerances, “Piercing on the fly” can be used. In this mode, the laser cutter head does not move to the precise piercing height. In this case a significant improvement in cycle time can be achieved in the expense of tolerance (± 2.5 mm) [7, 24].

As a rule of thumb, the cost of direct hot stamping followed by laser cutting can be calculated as shown in Fig. 7.10.

Fig. 7.11 Initial blank shape and final part geometry. Red line shows the areas to be laser trimmed: **a** Iteration 1 starts with a rectangular blank, **b** iteration 2, and **c** final iteration where no laser trimming is required (re-created after [28])



Since laser trimming is still a big part of the cost pie, several methods are developed to reduce—if not totally replace—the need for laser trimming. Alternative trimming methods are explained in the next section.

7.2.3 Alternative Cutting Methods

7.2.3.1 Blank Development

Blank development is designing the initial blank geometry such that no trimming would be necessary after forming/drawing operations, as shown in Fig. 7.11. The method is typically applicable for areas with $\pm 2 \dots 3$ mm tolerances. In automotive applications several areas could accommodate such large tolerances, including (1) overlapping flanges for spot welding and (2) holes used for e-coat drainage, weld electrode access, or cables [22, 27].

The achievable tolerance level depends on (1) positioning of the blank on the hot-forming die and (2) geometry requirement in the final part. It is essential to locate the blank through two locating holes in the blank [22, 26]. Currently, commercially available simulation software can handle the blank shape optimization through an iterative calculation [29, 30]. A study in 2015 has proven that through simulation the maximum deviation between the desired final part geometry and the hot-stamped part was in the order of 1.21...1.67 mm depending on the edge geometry [26]. Blank development together with nesting optimization could reduce the trimming cost and material cost together (see Fig. 7.10).

7.2.3.2 Hot Cutting

In (in-die) hot cutting process, the trimming/piercing operations are done at the same die set that hot stamps the part. According to Koroschetz et al., there are two different die designs for hot cutting [26]:

1. Hot cutting before forming, using cutting blades,
2. Hot cutting after forming is completed. This one requires actuators.

Hot cutting is limited to areas where the cutting plane is close to 90° . For this reason, not all trimmings and piercings may be suitable for hot cutting process [31]. Although using cams for side piercings have been tried, typically hot cutting is limited $\pm 10^\circ$ angle from the bolster plane [32, 33].

The first method has a simpler die design, but the flanges may draw-in and/or shrink (due to temperature and also microstructural changes). Thus, the tolerances in the flange geometry depends very much on the process and the die design [26].

Since 2011, Honda is using hot cutting in series production. The cutting is done, however, after the part forming is completed, before the quenching. Thus, the material would be softer to cut, causing much less die stress and press force [34].

One of the most major problems in hot cutting after forming - especially in piercing—is the shrinkage of the blank. As the blank is simultaneously being cooled at a rate over 27°C/s (49°F/s) while cutting is performed, the blank would shrink in size. Considering the clearances are 5...15% of the material thickness, the punch must be moved out very quickly once the piercing is completed. For this reason, very fast hydraulic actuators are advised [34–36].

Hot cutting could reduce the cost of the total process by reducing the cycle time, work-in progress and capital investment. Although the main reason for in-die hot cutting was to reduce a secondary step, either it be a laser trim or hard trim process; there are more advantages of hot cutting. Matsuno et al. found that around the hot sheared edge, finer grains of ferrite are formed and thus delayed fracture is prevented [37]. According to a recent study, the optimum process parameters are cutting around $\sim 550^\circ\text{C}$ (1020°F) and with 5% clearance [36].

Because of the limitation of cutting angle and the requirement of expensive actuators, hot trimming is typically used in conjunction with other methods. This is explained in detail in Sect. 7.2.3.7.

7.2.3.3 Hot “Half” Cutting

A modification to hot cutting is, hot “half” cutting, in which the process is not completed and the slug is not removed from the blank. Although the word “Half” may suggest that 50% of the thickness is sheared, it may be possible to shear between 10 and 70% of the thickness [37]. The engineers who had developed this technology claims that the technique is a practical solution to difficulty of slug (scrap) removal in the hot cutting process. The slugs are later sheared by hard cutting, as shown in Fig. 7.12 [33, 38, 39].

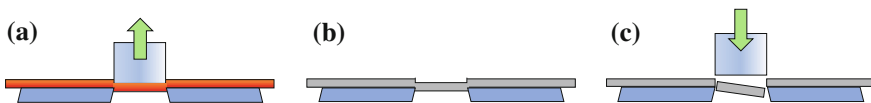


Fig. 7.12 Schematic of hot half cutting: **a** the cutting is done in hot condition but interrupted before the slug is separated, **b** once the part is cooled, **c** it is then hard cut (re-created after [38])

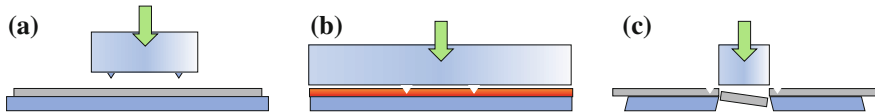


Fig. 7.13 Schematic of cutting with notch: **a** the notch is formed before the **b** hot-stamping process. **c** The blank is then hard cut (re-created after [10])

It was also shown that by hot “half” cutting, the cutting forces in the final hard cutting Fig. 7.12c can be reduced by almost 50%, whereas the energy requirement was reduced by over 80% [38].

7.2.3.4 Cutting with Notch

Another method proposed to reduce the cutting forces and sheared edge damage, is cutting with notch. In this method, a preforming is done to form notch along the cutting line, while the blank is still in as-delivered condition (in Ferritic-Pearlitic phase). The blank is then hot stamped and quenched. The process, depending on the notch direction (upside or downside) can be used to generate burr-free edge and/or to reduce the cutting forces in hard cutting [10] (Fig. 7.13).

7.2.3.5 Cutting Soft Zones

Please see Sect. 8.4.3.

7.2.3.6 Adiabatic Cutting

A typical hard cutting press would typically operate around 25...100 mm/s (1...4 in/s). The plastic deformation in the shear zone generates some heat. When cutting is done with at very high press speeds, over 3 m/s (120 in/s), the heat produced would not have time to dissipate. Thus, temperature increases very rapidly in a very narrow shear band ($\sim 100 \mu\text{m} \sim 4000 \mu\text{in}$ in thickness) for a very short time (less than 100 μs), as shown in Fig. 7.3e. With increased temperature, the material softens, much faster than it strain hardens [25, 40–42].

By using adiabatic cutting, it is possible to get [43, 44]:

1. Almost no burr and very smooth cut edge,
2. Uniform hardness distribution throughout the edge,
3. Very low cycle times, high productivity if the process could be automated,
4. Can be used both for piercing and trimming,
5. No lubricants are required and tool wear is reduced.

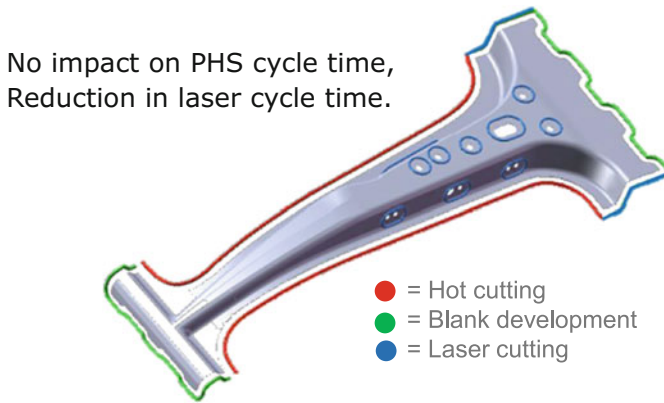


Fig. 7.14 Combining different trimming techniques would reduce the laser cutting length (and thus the laser cycle time), without affecting PHS cycle time (re-created after [44])

Presses that are capable of adiabatic cutting are already commercially available. However, the technique is still not in mass production.

7.2.3.7 Combination of Different Cutting Methods

As discussed in earlier sections, each and every cutting methods has its own advantages and limitations. Even in a single component, it is possible that several holes or outlines could not be hot trimmed (due to geometric limitations). For assembly reasons, some dimensions may have tighter tolerances than others. Thus, it may not be feasible to avoid laser cutting or use only one alternative cutting method.

As discussed in laser trimming section, a typical B-pillar may require as long as 6 m (20 ft) of trimming and piercing. Depending on the thickness of the part and the geometry, trimming of 6 m (20 ft) would typically around 45 s. However, by combining different cutting methods, it may be possible to reduce the laser cut length; and thus, the cycle time in laser cutting. An example B-pillar is shown in Fig. 7.14 [24, 44].

7.3 Surface Conditioning

Uncoated and Zn-coated blanks may have a thin oxide layer, even if protective atmosphere were used in the furnace, Fig. 7.15b. This layer may have iron oxides in the uncoated blanks, and zinc oxide in Zn-coated blanks. These oxides must be removed before welding and painting, Fig. 7.15c. To achieve this, sandblasting, shot blasting or dry-ice (CO_2) blasting is typically used [45–47]. According to a recent

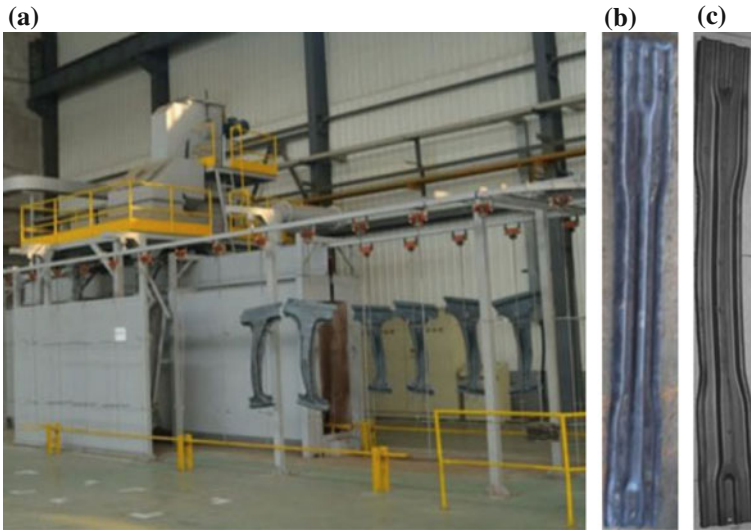


Fig. 7.15 a A shot blasting line for hot stamping, b an uncoated door beam with scale, c the same door beam after shot blasting [4]

study, uncoated and Zn-coated blanks are approximately 22% of the market (uncoated $\sim 15\%$, Zn-coated $\sim 7\%$) [48].

In shot blasting, small diameter steel balls (0.05...0.3 mm, 2...12 μin) are blown by compressed air. In sandblasting on the other hand, corundum or similar materials are used. Pressure levels are typically around 4–20 bars ($\sim 60\text{...}300$ *psi*) [49–51]. The impact from the blasting removes the brittle oxide layer. The process may also introduce some compressive stress. Shot blasting may cause deformation on the thin sheets, and thus may be detrimental to tolerances [46, 52]. A typical sandblasting line is shown in Fig. 7.15a.

After the scale is removed bare steel would be exposed. To prevent oxidation, oiling or coating may be applied [52].

7.4 Quality Control

In conventional cold stamping, the manufacturer receives material and forms the part into the desired geometric shape specified from the customer. The quality department for a cold-stamp operation monitors dimensional results to ensure that part geometry stays within specification set forth by the customer drawing. Quality also ensures that parts do not have any material defects due to bad forming conditions. Splits, excessive thinning, and burrs on trim edges are some of the most common defects that are inherent in the forming process as the production tool wears.

It is important to remember that the hot-stamping process creates both, the geometric part shape and the final material properties. Due to this, manufacturers require additional quality controls which monitor all of the specifications for cold stamping as well as material properties of the final product. The quality department for hot-stamping manufacturers are usually split into two distinct groups, where one is in charge of ensuring parts meet dimensional specifications, and the other is in charge of ensuring that part material properties meet specifications.

This section will be exploring how manufacturers can control dimensional quality throughout the entire hot-stamping process (stamping and post-processing), and how manufacturers can monitor the final material properties of their products.

The mainstream manufacturing process for hot-stamping is usually comprised of the below manufacturing steps. It is important to understand how all of these manufacturing process can impact the final product, and how to monitor and control quality throughout all processes:

- Blanking—cutting a shape from the raw material, which prepares the blank for the heating and stamping process
- Preforming (only in the indirect hot-stamping process)—this is a cold-stamping process which creates part of the geometric shape before the heat-treat, and hot-stamp process.
- Hot-Stamping—the process of heat treating the blank while simultaneously stamping it, creating part form and material characteristics
- Post-Processing—due to the hardness of the material, the part needs to go through post-processing to add any features which need to be held to tight dimensional tolerances
 - Laser Cutting—this is the most common post-processing manufacturing method.
 - Cold Piercing /Trimming—this is another option of adding tight tolerance features but is less popular.

7.4.1 Blanking Quality

Blanking sets the dimensions of any features of the part that is used to locate the hot steel in the hot-stamping die. The blank dimensions need to be precise enough to not interfere with features in the hot-stamp die (such as peripheral guides, etc.). Any hole features placed in the blank and carried through to final product are also set during blanking. The two biggest quality concerns in blanking are (1) Wear in cutting tools (creating excessive burrs in blanks). Keeping the cutting tools and punches sharp and maintained will ensure that the blanks do not form excessive burrs that can cause hinders in the hot-stamping process. It will also ensure that any holes carrying through to the hot-stamp tool and final part will be kept to the correct size (as pins wear, the hole diameter in the metal shrinks). (2) Inconsistent pitch from the raw material feed. Keeping the pitch consistent will ensure that blank fits between peripheral guides, and that hole dimensions are always in the same relative

position to each other as well as trim lines. The final blank shape can be controlled by building a simple jig capturing blank trim. This ensures that there is consistent pitch during the blank stamping process, and that the blank is ok to progress to the next manufacturing process.

7.4.2 *Preforming Quality*

Preforming is a cold-stamping process and therefore requires all normal quality procedures one would have in a cold-stamp process. With this process, we also need to consider both, the metallurgical component of this operation as well as the dimensional process.

Metallurgical: The most common quality issue one has to control in preforming are surface quality conditions in the steel substrate and in coatings. As with the steel, the part suppliers also produce the final properties of coatings. Different coatings on the steel display various behaviors during the preforming and heating processes. It is important that the preforming process does not remove any coating during the cold-stamping process. Cracks, flaking, and other surface conditions can negatively affect the behavior of coatings on steel before the heat treating and hot-stamping processes. These conditions are unique to part geometry and coating type, and need to be evaluated before production. Surface defects of the steel substrate during preforming can negatively affect metallurgical results of the final hot-stamp product as well, and need to be monitored visually throughout production.

Dimensional: Dimensional properties of the preformed part need to match the predicted shape before moving on to the next operation. The cold-stamp operation usually sets most of the part geometry before moving to hot-stamping for final material properties. It is recommended to have checking fixtures and regular quality control of part dimensions before moving forward to the hot-stamping operation.

7.4.3 *Hot-Forming Quality*

As mentioned before, the hot-stamping operation is responsible for both, the final form geometry of the part, and the final material properties of the steel substrates and its' coating.

Dimensional: The hot-stamping die is responsible for all of the final form dimensions. Normally, none of the form is influenced by any of the post-processing manufacturing steps. Since the final locating features of the part are created in a later manufacturing operation, it can be difficult to check the dimensional quality of the part's form geometry. To check form in a repeatable manner before final locating features, manufacturers either build a simple holding fixture, or scan parts to final part geometry.

Holding fixtures use a combination of rough locating holes and form to locate the part in a positive manner. Since hole-geometry distorts during hot forming, any holes not pierced during hot forming cannot be used as final locating features. This means that the rough locator holes used for holding or “in-process” fixtures usually get removed during the laser process as they are no use to the customer. This also means that it is difficult to check parts after hot-stamping due to not having final locating features in the parts.

Scanning equipment can also be used to check part geometry off the hot-stamping die. There are different type of scanners, but in general, the scanning equipment is able to pickup all form geometry points. The operator can then fit the actual scanned results to the theoretical CAD model to understand if any form geometry is off location.

It is important for manufacturers to come up with a part check strategy after hot-stamping, as the part’s final geometric form is set in the hot-stamp die.

Metallurgical: Since final material properties are created during the hot-stamping operation, it is important to keep tight quality control on material properties for all parts produced. Every hot-stamp die has a unique operating recipe associated with it which ensures that desired dimensional properties and material properties are achieved. This recipe is determined with much testing before production start, and needs to be set-up with a big enough operating window for production equipment to keep up with the required processing times.

Hot-stamping equipment has many redundant systems measuring all applicable process parameters throughout the production process. Due to these, it is assumed that the production environment is stable and that all part processed meet the processing parameters set forth in the die operating recipe. Due to the critical nature of these parts, manufacturers due to random sampling of parts to ensure that everything produced meets material specifications. A sampling schedule needs to be set-up unique to each manufacturer to ensure that all production shifts have adequate amount of testing. At a minimum parts shall be tested close to the beginning of run to ensure that tooling was set-up correctly, in the middle of the run to ensure that nothing has changed, and at the end of run for verification. Testing frequencies and sample sizes need to take production run sizes, die cavities, and number of ovens into account when being created. It is important to collect parts form all production streams (such as different die cavities of same part, different ovens or oven cavities, etc.) oversampling lifetime. For example, one should never just test parts out of the same oven and die cavities if there are more than one.

All sample parts need to have a full metallurgical evaluation before shipments are released to the customer. To ensure that properties are achieved throughout the entire part, samples are tested at both micro and macro levels. Common tests that are evaluated at the manufacturers are:

- Hardness → Macro and Micro Level
- Tensile Test → Yield Strength, Ultimate Strength, and Elongation
- Microstructure → Check to see if basic martensite microstructure is achieved
- Coating Evaluation → check to see if coating is intact, and if it is properly alloyed.

Table 7.1 Common joining method for hot-stamped steel to other parent metals (re-created after [53–55])

Parent metal	Most common method	Alternative methods
Cold-formed sheet steel	RSW	Arc Welding
Hot-formed sheet steel	RSW	Arc Welding
Aluminum sheet	Resistance Element Welding + adhesive bonding	Element Arc Welding
		Friction Element Welding
		Hemming
		Special riveting in soft zone
Aluminum Profile	Screwing with pre-punched holes + adhesive bonding	Resistance Element Welding + adhesive bonding

7.5 Welding and Assembly

A typical car body consists of 250...400 steel sheets joined together. In the recent years, die-cast, extruded or sheet aluminum are also increasingly used. The main joining method of automotive industry is “Resistance Spot Welding” (RSW). In the last decade, brazing, adhesive bonding, mechanical joinings (clinching, flow drill screws, rivets, etc.) and resistance element welding are getting more popular with multi-material-mix car bodies which contain steel and aluminum components joined together [53].

Table 7.1 shows the most common welding methods to weld hot-stamped steel to other metals.

7.5.1 Resistance Spot Welding

In resistance spot welding, two or three similar materials (i.e., steel to steel) can be welded using two electrodes. As shown in Fig. 7.16, a typical cycle has four stages and three variables: (1) clamping force (F), (2) current (I), and (3) cycle times (t) [56].

The typical RSW process window is shown in Fig. 7.17a. The minimum welding current (I_{min}) is typically defined by the weld nugget diameter being around $4\sqrt{t}$ or by a defined minimum shear strength of the weld, Fig. 7.17b. The maximum current (I_{max}) is decided by the expulsion. Expulsion can be defined as a spot welding defect, in which, the molten metal is ejected from the parent metals. The range between the minimum and maximum current is called as “welding current range”, and for automotive applications, it is advised to be equal to or over 2 kA [49, 52, 58, 59].

Due to high carbon equivalence of 22MnB5, the current range is typically low. To improve current range, two-pulse (also known as Waveform control) welding can be

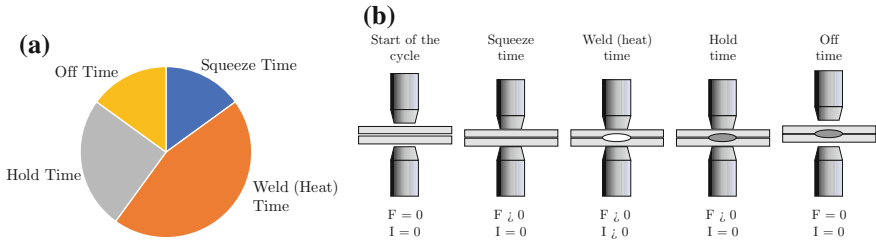


Fig. 7.16 Resistance spot welding: **a** approximate cycle times, **b** electrodes in each cycle (re-created after [57])

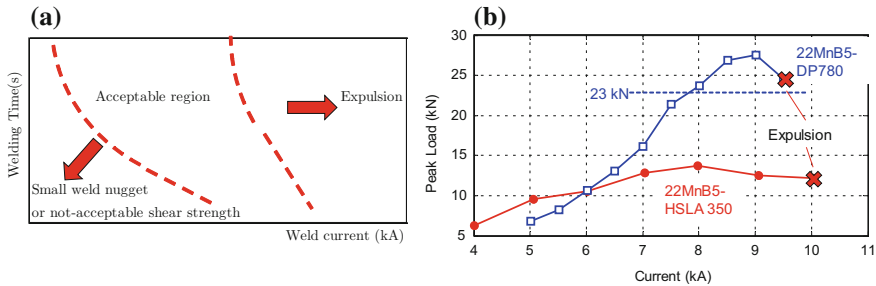


Fig. 7.17 **a** Resistance spot weld parameters and acceptable region (re-created after [59]), **b** peak load the weld can carry is a function of weld current (re-created after [60, 61])

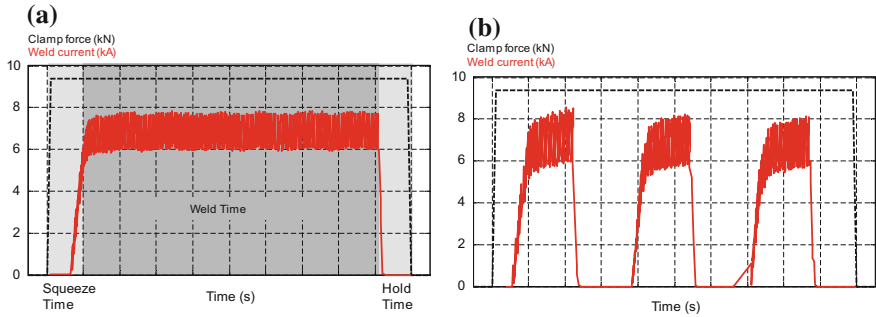


Fig. 7.18 Current and clamp force versus time graphs of (1) single-pulse weld cycle, (2) waveform control with three pulses (re-created after [59])

used. In this method, the clamp force is not removed while the current is turned on and off. Figure 7.18a shows a single-pulse weld cycle, and b shows a three-pulses weld cycle [47, 59].

In resistance welding of hot-stamped steels, (1) coating thickness (especially interdiffusion layer), (2) existence of surface oxides, and (3) final hardness are three important factors. The first two items would change the resistance of the stack, whereas the final hardness is important as it is a result of the microstructure [47, 52].

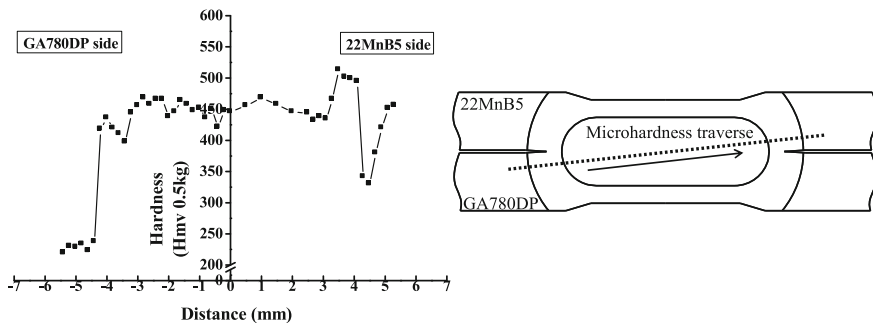


Fig. 7.19 Hardness distribution in a spot weld between AlSi coated 22MnB5 and DP780 GA [60]

A study with tailored tempered Zn-coated blanks showed that with a two-pulse method, a weld current range of 1.7 kA could be found for samples that are annealed at between 650...910 °C (1200...1670 °F). Spot welding was applied after dry-ice blasting. The weld strength was measured right after welding and also after a 10 weeks of VDA 621-425 corrosion test—to simulate lifetime of a vehicle. Results have shown that in the tailored areas (i.e., not heated over 910 °C (1670 °F)) had 12...25% higher weld strength after VDA test [47].

When hot-stamped steel is welded to cold-formed automotive steel, there would be a heat affected, softened zone. Still, since most automotive steels are much softer than this zone. In a study by Choi et al., AlSi coated 22MnB5 was spot welded to DP 780 GA. The weld's strength (i.e., peak load) versus weld current can be seen in Fig. 7.17b. The hardness distribution in the weld is shown in Fig. 7.19 [60] (Fig. 7.20).

When 22MnB5 is welded to another 22MnB5 steel, the weakest point (i.e., the lowest hardness value) in the assembly becomes the heat-affected zone (HAZ). A study in Sweden showed that when 22MnB5 is spot welded to another 22MnB5, the base materials would have almost constant 500HV hardness, whereas in the weld zone the hardness may be as low as 350HV. When such a welded assembly is tensile tested, it would always fail at the weld zone [62]. Another study has shown that spot welds are acting as “metallurgical notches”, an analogy to holes and pierces acting as “geometric notches”. A hot-stamped steel bumper beam with no holes and welds would absorb more energy without fracture whereas when a spot weld or a hole is introduced a sudden failure would be observed and the energy absorption capacity is significantly reduced, Fig. 7.21 [63].

7.5.2 Arc Welding

As seen in Table 7.1, the second most common method to weld hot-stamped steel to another steel is “arc welding”. In automotive industry, arc welding is used in blind

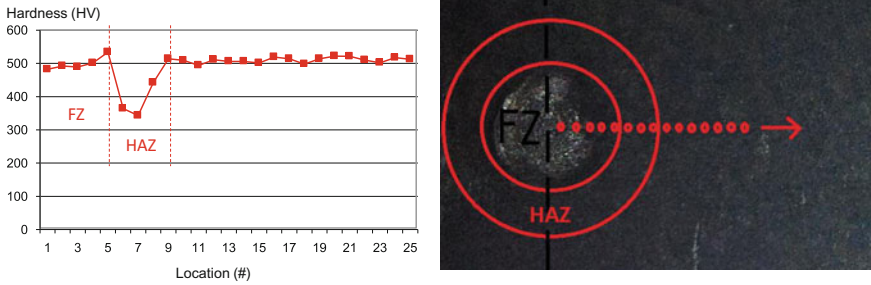
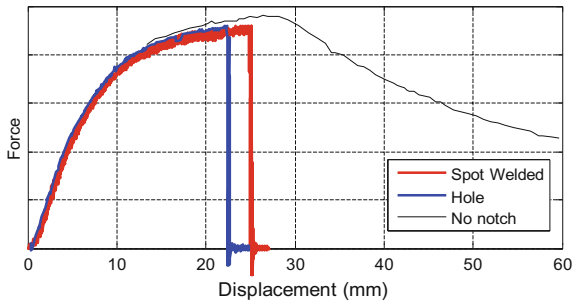


Fig. 7.20 HAZ softening when 22MnB5 is spot welded to 22MnB5 [62]

Fig. 7.21 Notches reduce the energy absorption of hot-stamped parts and cause sudden failure. A spot weld would act as a “metallurgical notch” [63]



areas (i.e., accessible only from one side). In this method, electric current is used to melt a consumable electrode [53, 64].

In arc welding of hot-stamped steel to common automotive steels, it was found that there would be a softened area in the heat affected zone (HAZ). As shown in Fig. 7.22a and b, when AlSi- coated 22MnB5 is arc welded to uncoated DP 600 or DP 780, the softest (weakest) point is still in the DP steel. Thus, both in fatigue and static tests, the assembly mostly fails from the soft steel [65, 66].

7.5.3 Other Joining Methods

Recently multi-material mix vehicles are getting more and more common. In these vehicles, not only steel, but also aluminum, carbon fiber, magnesium, and polymers may be used in the car body. It has to be noted that vehicles with aluminum bumpers, doors and closures cannot be classified as multi-material mix, as these components are assembled with bolts (also known as bolt-on components) and are not welded or mechanically joined.

As listed in Table 7.1, for aluminum to hot-stamped steel joinings, resistance element welding is one of the most studied methods and also in mass production for joining aluminum and steel (not necessarily hot stamped) [67, 68].

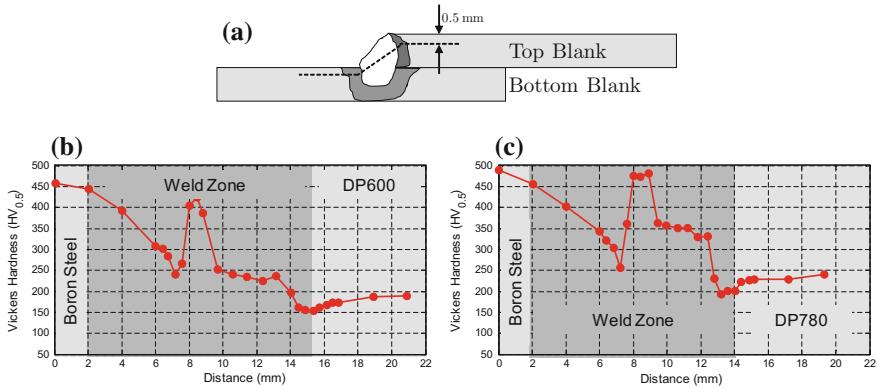


Fig. 7.22 a Schematic view of an arc welded lap joint; hardness profile over the dashed line in: **b** DP600-22MnB5, **c** DP780-22MnB5 welds (re-created after [65, 66])

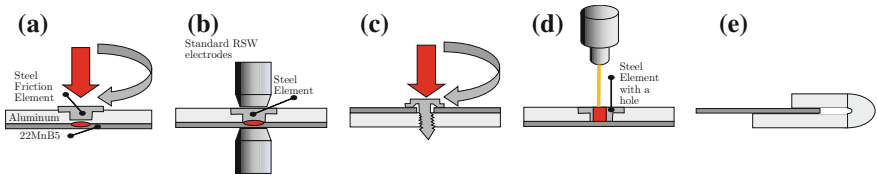


Fig. 7.23 Schematic views of alternative joining methods for hot-stamped steel and aluminum joints: **a** friction element welding, **b** resistance element welding, **c** flow drill screw, **d** element arc welding, **e** hemming (re-created after [55, 67, 70])

One of the earliest vehicles that had both hot-stamped components and aluminum structure was 3rd generation Audi A8 (SOP 2010). In this vehicle 92% of the body-in-white was aluminum, but the B-pillar reinforcement was hot-stamped steel. The hot-stamped reinforcement was spot welded to an HSLA 340 support plate. This plate which had pre-punched holes was later “flow drill screw” ed to the body side panel which was a 6000 series Aluminum (i.e., AlMgSi alloy) [69]. Since then several new methods have been proposed, as seen in Fig. 7.23.

Resistance element welding has been studied by researchers to join 22MnB5 to 6000 series aluminum [71, 72], and steel–polymer–steel sandwich material [56]. Element materials are steel, so that the spot welding is done between two “similar” materials. Several studies have shown elements made of S235 (Mild Steel), S355 (HSLA steel) and 20MnB4 can be welded to 22MnB5 steel [56, 71, 73].

Friction Element Welding is one of the proposed joining methods for hot-stamped steels and aluminum. Audi has been studying the technology since 2012 (if not earlier) [72]. In this method, a high strength steel (e.g., 23MnB4) element is pressed over the soft material (in most cases aluminum) and rotated. The friction creates a hole and generates heat and plasticity in the soft material. By the frictional heat, the steel element is then welded to the base steel (22MnB5), Fig. 7.23a [73]. The system does

not require a precut holes, as opposed to resistance element welding. According to [72], friction element welds may carry over 2.5 times more load, compared to resistance element welded assembly. Thus, with increased load capacity per joint, less number of joints may be feasible. On the negative side, the method requires two side accessibility and leaves 2...3 mm elevation on the application side [72]. The process is already in mass production at Audi with 2nd generation Q7 (SOP 2015) and 4th generation A8 (SOP 2017). The technique is used to join hot-stamped steel to aluminum sheets and castings [54, 55]. Due to heat generated, hot-stamped steel is tempered around the element. A study has found that hardness may drop from $\sim 500\text{ HV}$ to $\sim 300\text{ HV}$ in the heat affected zone [72].

Flow drill screws can be used to join ultra-high strength steels (up to 1000 MPa (145ksi) tensile strength) to aluminum extrusions and castings. In this method, a high strength screw is used to penetrate and thread the materials to be joined, Fig. 7.23c. While threading, fastening is also done [74]. However, as of today, the hardness of screws are not enough to penetrate hot-stamped steel [75, 76]. When flow drill screws are used with steels over 700 MPa tensile strength, a pre-pierced hole may be required [68].

A relatively recent solution to join hot-stamped steel to is called “Element arc welding”. As seen in Fig. 7.23d, aluminum is first pierced and a steel element with a hole is placed. The element is arc welded to base metal (could be any high strength steel, including hot-stamped steel). The process does not require two-sided accessibility and can be applied both to profiles and sheets. The researchers have shown that 22MnB5 can be welded to 6000 series aluminum with a very high shear strength [70].

References

1. E. Billur, H. Porzner, D. Lorenz, M. Holeček, M. Vrojlik, M. Hoss, B. Damenha, J. Friberg, C. Koroschetz, M. Skrikerud, From concept to virtual reality: Virtual hot forming engineering, in *5th International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Toronto, ON, Canada* (2015), pp. 463–470
2. J. Karlsson, Press requirements. Presented at AP&T Press Hardening, Next Step Seminar, Novi, MI, September 15th (2010)
3. F. Geyer, Strong metal, light cutting. *The Fabricator* (2013), pp. 64–65
4. P. Hu, L. Ying, B. He, *Hot Stamping Technology and the Main Equipment* (Springer, Singapore, 2017), pp. 19–44
5. J. Aspacher, Press hardening - “dead end” or “take off”, in *Presented at 25th European Car Body Conference, March 13-14, Bad Nauheim, Germany* (2007)
6. P. Belanger, New Zn multistep hot stamping innovation. Presented at Great Designs in Steel 2017 (2017)
7. S. Kulp, Laser applications in manufacturing high strength body parts, in *Presented at European Automotive Laser Applications (EALA) 2014, February 11-12, Bad Nauheim, Germany* (2014)
8. J. Banik, Hot forming state-of-the-art and trends. Presented at Insight Edition Conference, September 20–21, Gothenburg, Sweden (2011)
9. D. Landgrebe, M. Putz, F. Schieck, A. Sterzing, A. Rennau, Towards efficient, interconnected and flexible value chains – examples and innovations from research on production technologies,

- in *Proceedings of 5th International Conference on Accuracy in Forming Technology (ICAFT 2015)* (2015), pp. 61–78
10. M. Feistle, M. Krininger, R. Golle, W. Volk, Notch shear cutting of press hardened steels, in *Sheet Metal 2015*, vol. 639 of *Key Engineering Materials* (Trans Tech Publications, 2015), pp. 477–484
 11. I. Laumann, T. Picas, M. Grané, D. Casellas, M.D. Riera, I. Valls, Hard cutting of tailored hardened 22MnB5, in *IDDRG, Graz, Austria (2010)* (2010), pp. 355–362
 12. R. Kolleck, W. Weiß, P. Mikoleizik, Cooling of tools for hot stamping applications, in *IDDRG, Graz, Austria (2010)* (2010), pp. 111–119
 13. J. Livezey, High performance coatings for stamping & forming, in *Seminar in the Ohio State University, Columbus, OH* (2010)
 14. D. Viale, R. Bhatnagar, G. Baron, P. Jousserand, M. Gomez, Optimization of stamping tools to process very high strength steels; comparison of cold work tool steels. Presented at Great Designs in Steel, Livonia, MI, May 18th (2011)
 15. D. Viale, J. Béguinot, F. Chenou, G. Baron, Optimizing microstructure for high toughness cold-work tool steels, in *Proceedings of the 6th International Tooling Conference* (2002), pp. 299–318
 16. I.O. Yilmaz, B. Kaftanoglu, T. Hacaloglu, M. Kilickan, Integration of press hardening with cold trimming, in *Proceedings of 5th International Conference on Accuracy in Forming Technology (ICAFT 2015)* (2015), pp. 349–356
 17. K. Nothhaft, J. Suh, M. Golle, I. Picas, D. Casellas, W. Volk, Shear cutting of press hardened steel: influence of punch chamfer on process forces, tool stresses and sheared edge qualities. *Prod. Eng. Res. Devel.* **6**(4), 413–420 (2012)
 18. J. Dykeman, Advanced high strength steel - recent progress, ongoing challenges, and future opportunities, in *International Symposium on New Developments in Advanced High-Strength Sheet Steels* (AIST, 2013), pp. 15–28
 19. I. Picas, R. Munoz, A. Lara, R. Hernández, D. Casellas, Effect of the cutting process in the mechanical and fatigue properties of press hardened 22MnB5 steel, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 85–92
 20. M. Fritz, Process optimization of laser cutting and in the heating process, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 239–245
 21. N.B. Dahotre, S. Harimkar, *Laser fabrication and machining of materials* (Springer Science & Business Media, 2008)
 22. J. Aspacher, D. Haller, Hot stamping part design and feasibility study with respect to functionality and optimization of production cost. Presented at Forming in Car Body Engineering 2014, September 24–25th, Bad Nauheim, Germany (2014)
 23. F. Rima, Hot forming pressroom. Presented at AP&T Press Hardening, Next Step Seminar, September 15, Novi, MI, (2010)
 24. Michael Fritz, Ralf Kohllöffel, Laser cutting of press-hardened vehicle body parts. *ATZproduktion worldwide* **5**(2), 18–23 (2012). Jun
 25. F. Schieck, High speed impact cutting (HSIC) for PHS components – challenges and potentials, in *6th PHS Suppliers Forum, Caryville, TN, USA* (2017), pp. 272–283
 26. C. Koroschetz, M. Skrikerud, R. Kristensson, L.-O. Jonsson, D. Lorenz, H. Porzner, M. Hoss, Cost effective trimming in hot stamping through the combination of accurate blank development, hot and laser cutting, in *5th International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Toronto, ON, Canada* (2015), pp. 617–628
 27. N.K. Akafuah, S. Poozesh, A. Salaimeh, G. Patrick, K. Lawler, K. Saito, Evolution of the automotive body coating process—a review. *Coatings* **6**(2), 24 (2016)
 28. C. Koroschetz, M. Skrikerud, Mit Hilfe von warmbeschnitt und plattengeometrie-optimierung zum effizienten warmformteil. Presented at Forum Stanztechnik 2014, November 11–12, Bochum, Germany (2014)
 29. esi Group. PAM-STAMP 2015.1 User Guide (2015)

30. AutoForm Engineering. AutoForm-Trim plus. *Product catalogue* (2017)
31. B. Osburg, G. Lengfeld, O. Straube, Innovation and globalization as a factor of success for global hotstamping growth, in *New Developments in Sheet Metal Forming Conference, Stuttgart, Germany* (2012), pp. 79–92
32. M. Alsmann, M. Goede, S. Kulp, M. Lalla, J. Patak, F. Russ, Hot Forming - State of the ART and Future Requirements at Volkswagen. Presented at Materials in Car Body Engineering 2014, May 13-14, Bad Nauheim, Germany (2014)
33. Hong-Seok Choi, Jun-Ho Shin, Jin-Gyu Han, Pan-Ki Seo, Byung-Min Kim, Dae-Cheol Ko, The effect of inclined angle and positioning on the sheared edge in mechanical trimming using hot half-trimming of 22mnb5. *Adv. Mater. Process. Technol.* **2**(2), 245–251 (2016)
34. K. Teshima, Challenges of high-efficiency hot forming processes at Honda. Presented at Forming in Car Body Engineering 2012, September 26-27, Bad Nauheim, Germany (2012)
35. K. Mori, P.F. Bariani, B.A. Behrens, A. Brosius, S. Bruschi, T. Maeno, M. Merklein, J. Yanagimoto, Hot stamping of ultra-high strength steel parts, in *CIRP Annals - Manufacturing Technology* (2017)
36. D. Kim, Y.-J. Jeon, H. Seok Choi, J. Kang, Y.-D. Kim, Y. Moo Heo, J. Deok Kim, S.-T. Won, An investigation of the trimming of boron nitride steel (22mnb5) during the die-quenching process. *Procedia Engineering* **207**, 1540–1545 (2017). International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom
37. Takashi Matsuno, Yoshihito Sekito, Kaoru Kawasaki, Microstructure characterization of fine grains near hot-sheared surface formed during hot-stamping process. *J. Mater. Process. Technol.* **229**, 570–581 (2016)
38. Hong-Seok Choi, Byung-Min Kim, Dong-Hwan Kim, Dae-Cheol Ko, Application of mechanical trimming to hot stamped 22mnb5 parts for energy saving. *Int. J. Precis. Eng. Manuf.* **15**(6), 1087–1093 (2014). Jun
39. K. ichiro Mori, T. Maeno, T. Suganami, M. Sakagami, Hot semi-punching of quenchant steel sheet. *Proc. Eng.* **81**, 1762–1767 (2014). 11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan
40. D. Landgrebe, J. Schönherr, N. Pierschel, S. Polster, A. Mosel, F. Schieck, New approaches for improved efficiency and flexibility in process chains of press hardening, in *ASME 2015 International Mechanical Engineering Congress and Exposition* (American Society of Mechanical Engineers, 2015), pp. V02AT02A033–V02AT02A033
41. S. Subramonian, Chapter 1: Blanking, in ed. by T. Altan, A.E. Tekkaya *Sheet Metal Forming - Processes and Applications* (ASM International, 2012), pp. 1–18
42. T. Childs, *Adiabatic Shearing in Metal Machining* (Springer, Berlin, 2014), pp. 27–33
43. D. Landgrebe, T. Barthel, F. Schieck, Trimming of flat and tubular components by high speed impact cutting (hsic), in *ASME 2017 International Mechanical Engineering Congress and Exposition* (American Society of Mechanical Engineers, 2017), pp. V002T02A066–V002T02A066
44. M. Skrikerud, Next generation of compact hot forming lines for optimised throughput with different materials. Presented at Materials in Car Body Engineering 2013, May 7-8, Bad Nauheim, Germany (2013)
45. W. Fristad, New coil-applied coating for press-hardening steel. *Proc. Galvatech* **2015**, 892–898 (2015)
46. J Wilsius, P Hein, R Kefferstein, Status and future trends of hot stamping of usibor 1500 p. Geiger, M.; Merklein, M.(Edtr.): Tagungsband zum, **1**, 83–101 (2006)
47. Thomas Manzenreiter, Martin Rosner, Thomas Kurz, Gerald Brugger, Reiner Kelsch, Dieter Hartmann, Andreas Sommer, Challenges and advantages in usage of zinc-coated, press-hardened components with tailored properties. *BHM Berg- und Hüttenmännische Monatshefte* **157**(3), 97–101 (2012). Mar
48. I.M. Gonzalez, O. Straube, Development of zinc coated parts for hotstamping, in *Proceedings of New Developments in Sheet Metal Forming Conference, Stuttgart, Germany* (2016), pp. 265–276

49. S. Hamamoto, H. Omori, T. Asai, N. Mizuta, N. Jimbo, T. Yamano, Steel sheets for highly productive hot stamping. *Kobelco Technol. Rev.* **35**, 39–44 (2017)
50. I. Garcia, Weight savings and crash resistance in door constructions through hot stamping of door outer panels. Presented at Doors and Closures in Car Body Engineering 2011, November 16–17, Bad Nauheim, Germany (2011)
51. D. Landgrebe, A. Albert, A. Paul, B. Domes, M. Prohl, 20 years of hydroforming experience at the fraunhofer iwu – innovative process variants, in *Proceedings of New Developments in Sheet Metal Forming Conference, Stuttgart, Germany* (2016), pp. 403–423
52. D.W. Fan, B.C. De Cooman, State of the knowledge on coating systems for hot stamped parts. *Steel Res. Int.* **83**(5), 412–433 (2012)
53. Jens Meschke, Jöm Tölle, Lutz Berger, Multi-material concept for a battery electric vehicle. *ATZ worldwide* **119**(11), 48–53 (2017)
54. T. Hämmerle, D. Hußmann, The new Audi A8. Presented at EuroCarBody 2017, October 17–19, Bad Neuheim, Germany (2017)
55. T. Hambrech, The new Audi Q7. Presented at EuroCarBody 2015, October 20–22, Bad Nauheim, Germany (2015)
56. N. Holtschke, K. Nagel, Short-term resistance spot welding in connection with high-dynamic actuators. Presented at Joining in Car Body Engineering, April 5, Bad Nauheim, Germany (2017)
57. Miller Electric Manufacturing Company. *Handbook of Resistance Spot Welding* (2012)
58. H. Zhang, J. Senkara, *Resistance Welding: Fundamentals and Applications* (CRC press, 2011)
59. I. Sung Hwang, M. Jin Kang, D. Cheol Kim, Expulsion reduction in resistance spot welding by controlling of welding current waveform. *Proc. Eng.* **10**, 2775–2781 (2011). 11th International Conference on the Mechanical Behavior of Materials (ICM11)
60. H.S. Choi, G.H. Park, W.S. Lim, B. Kim, Evaluation of weldability for resistance spot welded single-lap joint between ga780dp and hot-stamped 22mnb5 steel sheets. *J. Mech. Sci. Technol.* **25**(6), 1543 (2011)
61. Xuebo Liang, Xinjian Yuan, Haodong Wang, Xiuyang Li, Ci Li, Xueyu Pan, Microstructure, mechanical properties and failure mechanisms of resistance spot welding joints between ultra high strength steel 22mnb5 and galvanized steel hsla350. *Int. J. Precis. Eng. Manuf.* **17**(12), 1659–1664 (2016). Dec
62. O. Hedegård, M. Åslund, Tempering of hot-formed steel using induction heating. Master's thesis at LTU Lulea Technic University (2011)
63. H. Lanzerath, Simulation: Enabler for the efficient design of lightweight boron intensive body structures. Presented at Insight Edition Conference, September 20–21, Gothenburg, Sweden (2011)
64. L. Morello, L.R. Rossini, G. Pia, A. Tonoli, *The Automotive Body: Volume I: Components Design*. Mechanical Engineering Series (Springer, Netherlands, 2011)
65. R. Koganti, S. Angotti, A. Joaquin, C. Jiang, Effect of materials stack-ups on fatigue performance of dp780 and aluminized coated boron steel gmaw lap joint, in *SAE Technical Paper*. SAE International. (2007)
66. R. Koganti, S. Angotti, A. Joaquin, C. Jiang, C. Karas, Effect of materials stack-ups and microhardness distribution on fatigue performance of dp600 and boron steel gmaw lap joint, in *SAE Technical Paper*. SAE International (2007)
67. H. Kurz, M. Goede, Requirements of sustainable automobile production for future material developments. Presented at Insight Edition Conference, December 10–11, Solihull, UK (2014)
68. G. Müllers, Achieving car body lightweight today and tomorrow - weight reduction as a result of substitution and combination. Presented at Strategies in Car Body Engineering 2015, March 17–18, Bad Nauheim, Germany (2015)
69. *The Art of Progress: Audi - The New A8* (2010)
70. R. Suzuki, K. Makii, New dissimilar metal spot joining process for aluminum and high-tensile-strength & ceq. steel based on the advantage of arc welding. Presented at Joining in Car Body Engineering, April 5, Bad Nauheim, Germany (2017)

71. Zhanxiang Ling, Yang Li, Zhen Luo, Yueqiao Feng, Zhengmin Wang, Resistance element welding of 6061 aluminum alloy to uncoated 22mnmob boron steel. *Mater. Manuf. Processes* **31**(16), 2174–2180 (2016)
72. U. Alber, Friction element welding - innovations for hybrid body parts. Presented at Joining in Car Body Engineering, April 19, Bad Nauheim, Germany (2012)
73. G. Meschut, O. Hahn, Joining technologies for multi-material design - a key to efficient future mobility. Presented at Materials in Car Body Engineering 2012, May 11, Bad Nauheim, Germany (2012)
74. S. Kurtenbach, X. Fang, T. Schlichting, A. Breidenbach, H. Dalhoff, M. Töller, Expansion of the applications from flow drill screwing by developing new high-strength elements. Presented at Automotive Engineering Congress, June 4, Nürnberg, Germany (2013)
75. J. Hover, Challenges of joining a boron-steel intensive body structure. Presented at Insight Edition Conference, September 20-21, Gothenburg, Sweden (2011)
76. S. Sinzel, N. Hornbostel, Expansion of the applications from flow drill screwing by developing new high-strength elements. Presented at Joining in Car Body Engineering, April 5, Bad Nauheim, Germany (2017)