# Chapter 5
# A Hot Stamping Line

**Jan Jonasson, Eren Billur and Aitor Ormaetxea**

**Abstract** Hot stamping requires a special production line, similar to but different than cold stamping operations. A typical hot stamping line consists of (1) a furnace/heating system, (2) a material handling system, (3) a press, and (4) an exit line. Sometimes trimming/piercing systems could also be included in the definition of "a line". In this chapter, the first three items are explained in detail.

## 5.1 Furnaces and Heating Systems

### *5.1.1 Conventional Roller Hearth Furnaces*

The hot stamping process begins with heating the blank over its austenitizing temperature (depending on the raw material, generally for 22MnB5, 950 °C (1750 °F). Although it is possible to heat the material using inductive and conductive methods, the most common method in application is to use the so-called roller hearth furnaces. The energy for heating can be supplied by gas or electric [1, 2].

One problem with the roller hearth furnaces is the total space they require. As seen in Fig. 5.1, the length of a furnace is a function of heating time ($t_{heating}$), cycle time ($t_{cycle}$) and the length of the batch ($L_{batch}$) and can be calculated by the Eq. 5.1. An example calculation for a B-pillar production is given in as well [1].

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E. Billur (ed.), *Hot Stamping of Ultra High-Strength Steels*,
https://doi.org/10.1007/978-3-319-98870-2_5

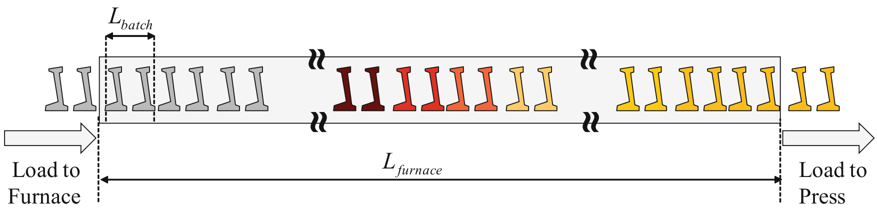



**Fig. 5.1** Determination of furnace length (recreated after [1])

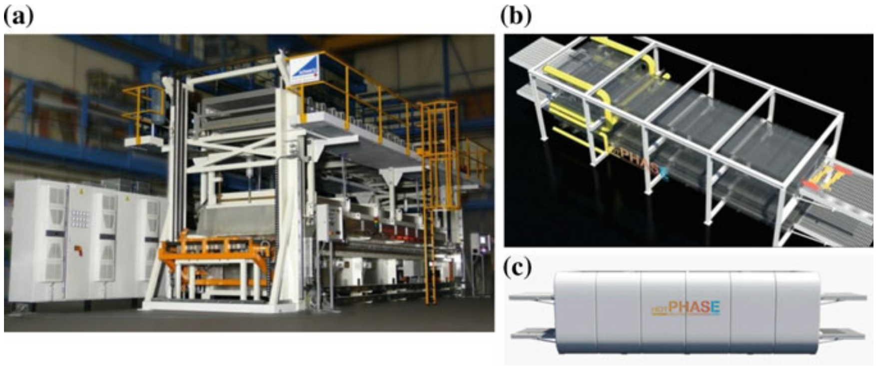


**Fig. 5.2** **a** Photo [1] and **b**, **c** schematics of a double-decker furnace [6]

$$L_{furnace} = \frac{t_{heating}}{t_{cycle}} L_{batch} \rightarrow \text{e.g.: } L_{furnace} = \frac{330\,\text{s}}{15\,\text{s}} 1.6\,\text{m} = 35.2\,\text{m} = 115.5\,\text{ft} \quad (5.1)$$

Several new furnaces have been introduced to save space and conserve energy. Some new furnaces are also capable to tailor the austenitizing process (i.e., keep some portions of the blank in Ferritic/Pearlitic phase) in order to tailor the final properties of the workpiece (as discussed in Chap. 8). In addition, it has to be noted that if the productivity is to be increased (i.e., cycle time $t_{cycle}$ is reduced), a longer furnace would be required [3, 4].

One of the designs to reduce the length of roller hearth furnace is a double-decker configuration, as shown in Fig. 5.2. The design can theoretically reduce the space requirement by half for the same production rate. A double-decker design, described by [5] reduced the furnace length from 57 m (187 ft) to 34 m (111 ft) for a process with cycle time of $t_{cycle} = 13\,\text{s}$.

Ebner Furnaces (Austria) has come up with the new furnace line called HotPHASE (Fig. 5.2b, c) which has two independent heating systems: (1) with natural gas and (2) electric. The furnace is capable of two heating modes:

**(1) Rapid heating** up with gas-fired furnace (Fig. 5.3a). The entrance zone of the furnace is heated to 1050 °C (∼1920 °F). This set temperature is over the austenitizing temperature of 22MnB5, the typical hot stamping material ($A_{c3} = 950\,°\text{C}$). Thus, a

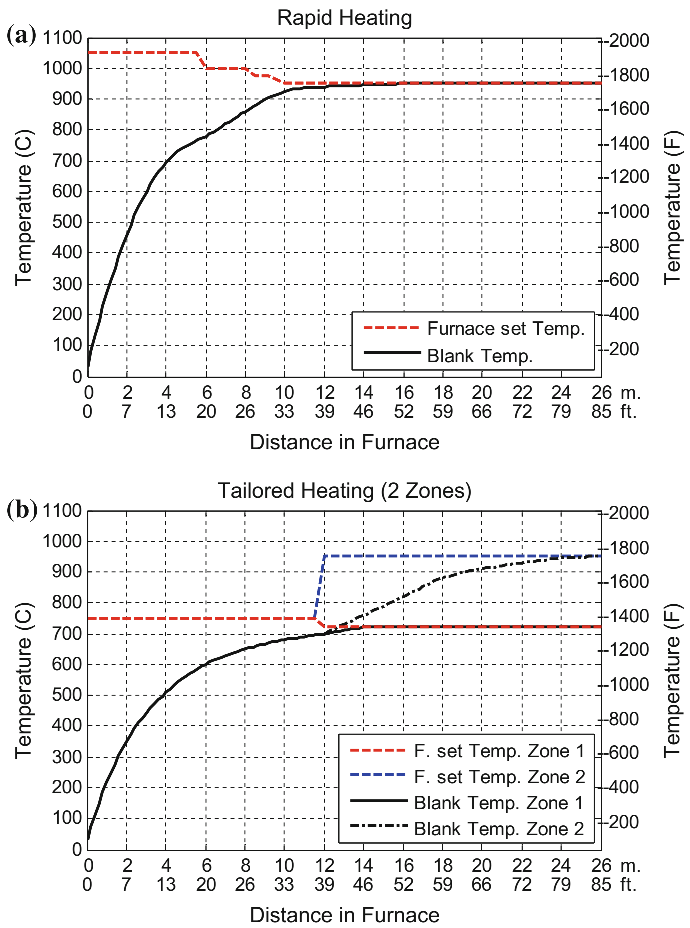



**Fig. 5.3** Ebner HotPHASE heating modes: **a** Uniform heating, **b** Tailored heating with two zones [recreated after [6]]

rapid heating can be obtained at the beginning of heating. Later, electric heating is used to sustain a more uniform distribution of temperature.

**(2) Tailored heating** is possible up to five different temperature zones (Fig. 5.3b). The furnace is heated by gas in the first section up to 750 °C (∼1380°F). Later sections are separately controlled. It is possible to keep some portions of the blank at around 725 °C (∼1350°F) in order to ensure that the sections of interest are not austenitized. The rest of the blank can be heated by local electric heaters up to 950 °C (∼1750 °F), and thus are austenitized [6].

**Fig. 5.4** AlSi coating builds up on ceramic rollers, if the blank is directly in contact with the rollers [7]

**Fig. 5.5** Exit area with blank centering [7, 9]

### *5.1.2 Roller Hearth Furnaces with Tray*

In typical roller hearth furnaces, the blanks may be placed on the ceramic rollers directly. In this case, the blank is only heated from the upper surface, which is suitable for thin blanks used in hot stamping process. The disadvantages of blank sitting on ceramic surfaces include the following:

(1) AlSi coating builds up on ceramic rollers, as shown in Fig. 5.4, causing them to be repaired or replaced frequently,

(2) Additional exit area with centering systems are needed (Fig. 5.5) which increase the space required and cycle time, as an additional centering operation has to be done [7, 8].

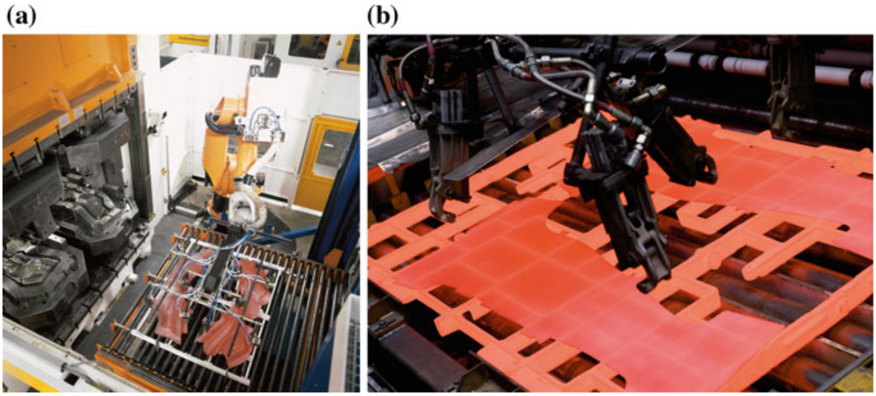



**Fig. 5.6** Use of trays with roller hearth furnaces in: **a** indirect hot stamping [11] and **b** direct hot stamping [12]

One solution to both these problems is to use a "tray" in the roller hearth furnace. The cold blanks can be placed over the trays, and thus the blank will not be in contact with the rollers. It is also easier to center at the exit. Trays can also be preferred in indirect hot stamping where the blanks are already preformed (Fig. 5.6a). Two disadvantages of using tray are [5]:

(1) A secondary conveyor is required to bring the trays back into the furnace entrance,
(2) The blank may lose some heat where it touches the tray (this is visible in Fig. 5.6b).

More importantly, preformed components (either indirect or hybrid hot stamping) cannot be heated in the furnace without a support, Fig. 5.6a. For this reason, furnaces with tray are used in all plants which hot stamp preformed parts [8, 10].

If the trays are not allowed to cool down during their way back, the temperature gradient between the tray and the blank would be reduced. By optimizing this temperature gradient, in a particular process, a reduction of 570 kW in installed power was realized [5].

### *5.1.3 Multi-chamber Furnaces*

Another furnace technique described by Eriksson, Multi-Chamber Furnace, reduces the space requirement and improves the control over the temperature. Here, each and every blank is placed in small furnaces and is heated for a predefined time. In a typical line, as illustrated in Fig. 5.7a, three fully automated robots are used [1, 5]:

(1) the first robot will take the blank from stack and place it in a buffer area,
(2) the second robot will take the blank from buffer area and put it in one of the furnace chambers,

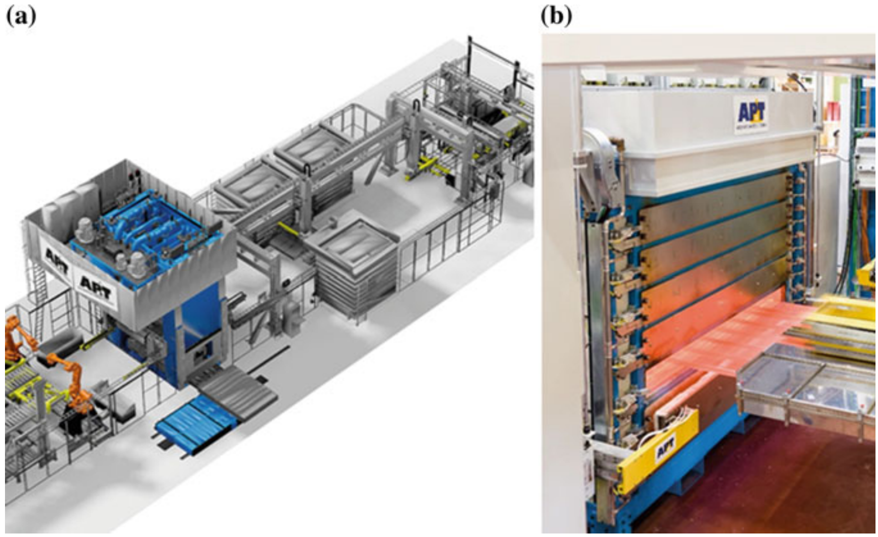


**Fig. 5.7** **a** an overall schematic of a hot stamping line with multi-chamber furnaces, **b** unloading a heated blank from the furnace

(3) the third one will pick the heated blank from the furnace and put it in the press (Fig. 5.7b).

According to Kahl, this technique has been used in Gestamp plants at least since 2004, if not earlier [13]. The number of chambers depends on the cycle time of the process ($t_{cycle}$) and the heating time of the blanks ($t_{heating}$) and can be calculated by Eq. 5.2:

$$n_{chamber} = \frac{t_{heating}}{t_{cycle}} \rightarrow \text{e.g.: } \frac{330s}{15s} = 22 \tag{5.2}$$

According to Eriksson for this particular case, the roller hearth furnace would require ∼35 m (115 ft) length (Eq. 5.1). However, a multi-chamber furnace would require 4–10 m (∼13–33 ft) length and 6–10 m (∼20–33 ft) width, depending on the layout [1].

### *5.1.4 Other Heating System Designs*

According to Behrens [14], heating systems can be classified into two groups: (1) external or indirect heating, and (2) internal or direct heating. The typical furnaces explained until this section are all classified as external heating. Internal or direct heating techniques include conductive (Figs. 5.8b and 5.9c) and inductive (Figs. 5.8c and 5.9d) heating methods.

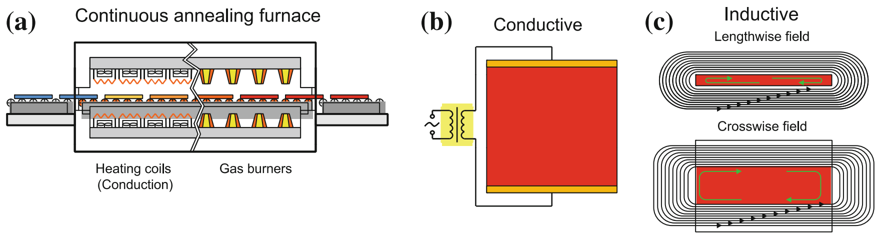



**Fig. 5.8** **a** External heating, using heating coils or gas burners in a roller hearth furnace; internal heating using **b** electric current, **c** induction [14]

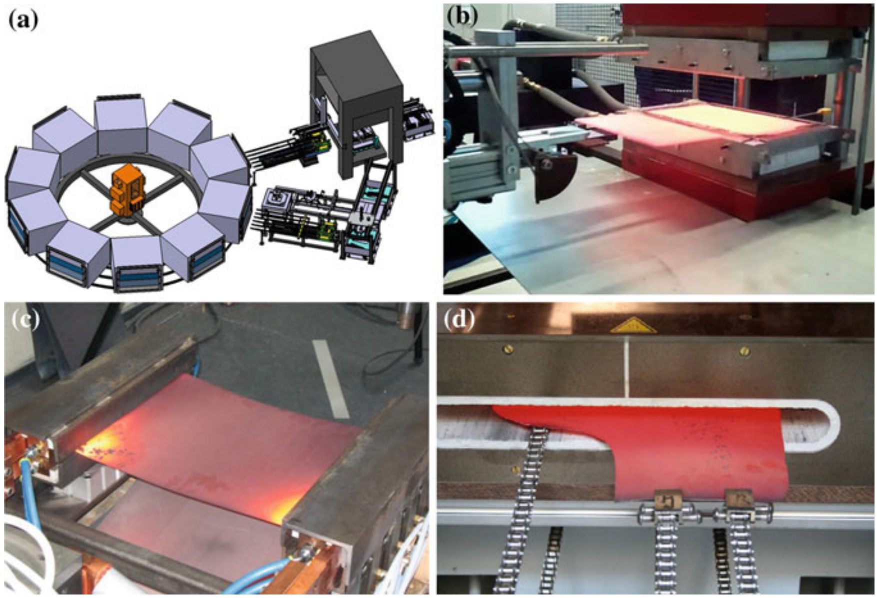



**Fig. 5.9** Heating methods under development and/or for use in prototyping: **a** rotary furnaces [16], **b** hot plate/contact heating technique [18], **c** conductive heating [14] and **d** inductive heating [22]

Currently, several types of furnaces are used in the industry such as a double-decker or multi-chamber furnaces as discussed in the earlier sections. Another method, that is being developed for mass production is called "rotary roof furnaces". One prototype of this type of furnace was set in Europe and being further tested, by Schuler [15]. Dalian University of Technology, in China, has also developed a rotary furnace as shown in Fig. 5.9a [16].

For prototyping purposes, hot plate heating or contact heating systems have been long used (Fig. 5.9b). In this heating technique, the blank sits on a flat heated die and is compressed with a second heated die. Using this method, it is possible to reduce the heating time. The heating cycle time is dependent on: (1) blank thickness, (2) temperature of the heated plates, (3) surface conditions and thermal contact conductance ($h_c$) (Sect. 10.2.4) of the blank and heated plates, and (4) heat capacitance of the heated plates [17]. According to Ploshikhin [18], austenitization time of 15 s was feasible with contact heating (no information about blank thickness). A more recent study by Holzweißig showed that 3 s heating time was not enough to austenite the 1.5 mm thick blanks, but 6 s was possible. They also found that quick heating strengthens the part: after 10 s contact heating and rapid quenching, the steel was found to have 1850 MPa UTS. Thus, the strength of the steel is increased approximately 20% compared to furnace heating. In this study, uncoated blanks were used so coating diffusion was not studied [17]. Rasera used AlSi-coated blanks with contact heating. For the coating diffusion to be complete, their design required 21 s heating time [19]. Recently, Fraunhofer IWU has developed a contact heating device that can tailor the heating. For tailoring final part properties (see Chap. 8), several portions could be held at approximately 650 °C (∼1200 °F). The system can heat 1.8 mm thick blanks in 15 s. Comparison of heating time of this technique with furnaces is given in Fig. 5.12a. As summarized in Table 5.1, contact heating does not have any geometric limitation and can heat the blanks to uniform temperatures [20]. Although it is a warm forming operation, in BMW i8 door beam production line, a similar heating system is used in production. Here the material was Aluminum 7075 alloy, and forming took place at 230 °C (∼450 °F) [21].

Conductive heating (also known as, resistance heating or Joule heating) is known to work well with constant cross section parts [14, 23]. However, when the blank's cross section is not constant and only two electrodes are used, local hot spots may occur as shown in Fig. 5.10a. Behrens developed a new method with multi-electrodes to control the heating in nonuniform sections, Fig. 5.10b. By controlling different sections, it was also possible to get a tailored heating for soft zones [14].

Mori showed that it was possible to heat 1.2 mm thick steels from room temperature to 800 °C (∼1500 °F) in only 2 s. Behrens showed that heating to 850 °C (∼1550 °F) took 16 s, and heating to 950 °C (∼1750 °F) took 20 s [14]. Both Mori and Behrens showed that rapid heating of uncoated blanks cause less scale formation compared to slow heating processes [14, 24]. Lee showed that heating rate of 100 °C/s (180°F/s) was possible, but caused AlSi coating to melt as shown in Fig. 5.11 [25].

One of the major drawbacks of conductive heating is that it cannot heat the area close to the conductors. Figure 5.12b shows that depending on the selected electrode geometry, areas close to the conductors were not fully hardened. Thus, the soft area could be trimmed and scrapped [26]. Liang showed that with a poorly designed conductor, the length of the unheated area may go up to 100 mm [27]. According to another study by the same group, thermal camera measurements show temperature at the contact point of electrodes were as low as ∼300 °C(∼570 °F) while 50 mm away the temperature of the blank was well over austenitization temperature ($A_{c3}$) [28].

Fast heating results in smaller grain sizes in martensitic structure and thus increases the strength and elongation at the same time [14, 30]. Liang showed that the tensile strength was increased ∼7% and total elongation was increased by ∼23% [28]. Senuma et al. used a slightly modified boron steel with higher Mn alloying

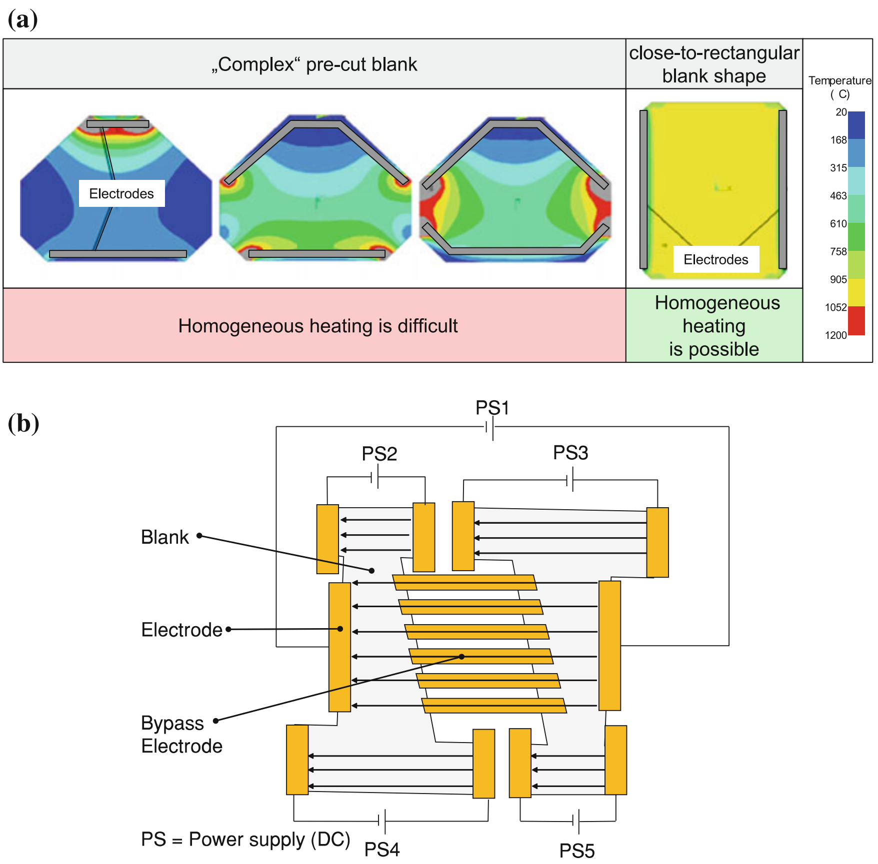



**Fig. 5.10** In conduction heating: **a** with only two electrodes, it is not possible to get homogeneous heat distribution on complex shapes [14], **b** using bypass electrodes and separate power supplies for different five regions, homogeneous heating may be possible (recreated after [20])

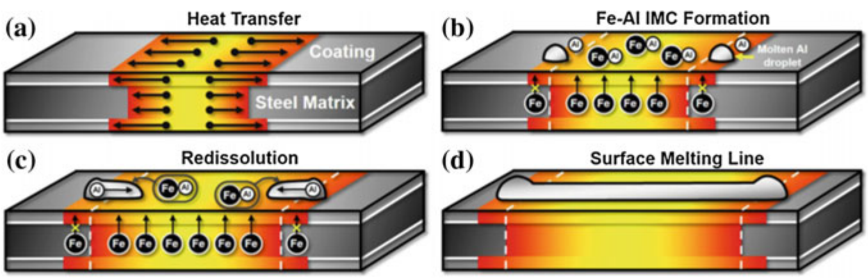



**Fig. 5.11** Formation of surface melting line of AlSi coating [25]

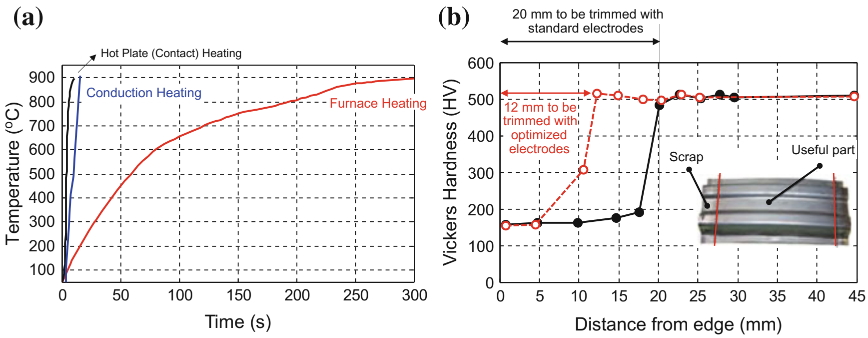



**Fig. 5.12** **a** Comparison of heating times of different heating techniques (recreated after [19, 26, 29]), **b** when conduction heating is used, depending on the geometry some portions have to be trimmed off (recreated after [26])

**Table 5.1** Summary of heating techniques [20]

| | Roller hearth furnace | Infrared | Induction | Resistance | Contact |
|---|---|---|---|---|---|
| Time to $A_3$ (s) | 300–360 | 50–70 | 20–30 | 5–10 | 15–30 |
| Temperature distribution | Uniform | Uniform | Depends on coil geometry | No heating at the ends (Fig. 5.12b) | Uniform |
| Blank shape | No limitation | No limitation | Close to rectangle | Only rectangle (unless special measures are taken) | No limitation |
| Space requirement ($m^2$) | 100–200 | 100–200 | 5–10 | 5–10 | 5–10 |
| Energy efficiency | Low | Low | Medium | High | Low |

(3 wt.% instead of 1.2 wt.% in 22MnB5), and found out that conduction heating increased the Charpy impact energy by threefold [31].

Conduction heating for press-hardening purposes had been patented many times [32, 33]. Currently, the technology is in mass production in Japan used in Lexus IS, since 2013. The parts produced are upper B-pillar reinforcement and cantrail, which have almost rectangular blank shapes. The process is used with Zn-coated blanks and surface conditioning (sandblasting, etc.) is not required [34].

### 5.1.5 Heating Time Reduction

There is also research going on how to reduce the heating time ($t_{heating}$). As of now, most of the production (with the typical material 22MnB5 and typical coating of 150 g/m$^2$ AlSi) require typically 5–6 min (300–360 s) in the furnace for the part to austenitize and the coating to diffuse. As shown in previous section, it is possible to austenitize the part in shorter time. However, homogeneous heating and the coating diffusion may require more time in the furnace. The coating diffusion is extremely important for most applications as it will affect: (1) weldability of the final part and (2) surface properties for painting [4]. Typically 30–420 s extra holding time is recommended for iron diffusion into AlSi coating [29].

If the time for heating could be shortened the initial investment and energy requirement for the furnace could be reduced drastically. Several alternative heating methods to reduce the time for heating ($t_{heating}$) include:

1. **Induction heating**: Induction heating is efficient and can heat the blank at a high rate ($\sim$ 70–100 °C/s, 125–180 °F/$s$) until Curie Temperature ($T_{Curie}$) which is around 740–760 °C ($\sim$1360–1400 °F) for 22MnB5. Both [35, 36] showed that heating up to Curie temperature would take 8–10 s. However, heating over $T_{Curie}$ to $A_{c3}$ has much lower efficiency. A possible solution was to use a more powerful face inductor to heat from $T_{Curie}$ to $A_{c3}$, but the total time would be still around 70 s and the temperature distribution would not be uniform [22]. Heating the blank by using only induction heating is not suitable for hot stamping applications, unless these issues could be addressed: (1) the AlSi coating would be liquidized and the coating thickness would not be constant [4, 35, 37], (2) the uniform temperature distribution cannot be established over Curie temperature [22, 36]. Coryell and Belanger came up with the idea of "pre-diffused" blanks. In this technique, the AlSi coating on the steel is first diffused in a furnace. Pre-diffused coated blanks are later used with induction heating in the hot stamping line [38].
2. **Induction heating + furnace**: Induction heating cannot be used to keep the temperature constant. One solution to obtain uniform temperature distribution with inductive heating is to use induction as a quick preheating (i.e., heat up to Curie Temperature in 8–10 s), and then to use conventional furnaces for further heating the blank to its austenitization temperature [36, 37]. According to [36], a total time of 70 s was enough to homogeneously heat a blank with induction preheating. The paper did not discuss about coating diffusion.
3. **Infrared Heating**: uses infrared rays to heat the blank and can be classified into two: (1) Near Infrared (NIR) heating uses 0.7–2.5 µm wavelength created by halogen lamps at 2000–2800 °C ($\sim$3600–5000 °F), whereas (2) Far Infrared (FIR) uses 4–1000 µm wavelength [20]. Siebert et al., showed that it is possible to austenitize AlSi coated blanks in 30 s using NIR. However, the parts had a three-layer coating instead of five-layers, to have a five-layer coating higher cycle time was required [4]. Recently, FIR heating has been studied in Japan. The efficiency of this system is lower compared to NIR, but achieving uniform temperature distribution is easier. The austenitization times for 1.6 mm thick blanks were

measured to be 50*s* for uncoated blanks and 70 s for AlSi coated blanks [20]. Recently, a multi-chamber furnace based on FIR technique has been patented [39].

4. **Fluidized Bed/Immersing Heating**: A fluidized bed heater uses fine solid particles (powders) which are made to behave like fluid by pumping air inside the bed. Uniform heating can be achieved at high heating rates [40]. In a 2011 study, uncoated 22MnB5 materials were heated using a fluidized bed filled with Aluminum oxide powder and heated to 900 °C (∼1830 °F). Experiments with uncoated 22MnB5 steels showed that the method may reduce ($t_{heating}$) from 160 s to 40 s for 1.2 mm thick steels, and from 240 to 80 s for 2.4 mm thick steels. If the fluidized bed is heated to 1000 °C (1832 °F) the time required to heat a 2.4 mm thick blank would be reduced to 26 s. It was also possible to tailor the final hardness by partial austenitizing. This was done by immersing the workpiece partly into the fluidized bed [41]. A similar concept of immersing the blank into liquid zinc was proposed to both austenitize and coat the blanks in one step [42]. Neither concepts are in mass production.
5. **Use of Thinner Coatings**: As the weight or thickness of the coating on the blank is increased, the time the coating takes to diffuse increases. Thus, the time needed in furnace can be reduced by the penalty of corrosion resistance [43]. The most common AlSi coating today is applied at 150 $g/m^2$ (abbreviated as AS150). Since the last few years an 80 $g/m^2$ coating is also available as an option [44] (abbreviated as AS80). Studies have shown that the dwell time of AS80 in the furnace can be 2–4 min, which is almost halved compared to 6 minutes of AS150 coating [45, 46]. In cyclic corrosion tests, samples with AS80 coated blanks had twice the blister width compared to AS150 coated ones. On the other hand, AS80 with an additional 1 $g/m^2$ ZnO coating was found to outperform AS150 [47].

## 5.2 Material Handling Systems

Once the blank is heated, it is very important to start the forming process as soon as possible to reduce the heat loss. Depending on the production rate and the initial investment, material handling may be done manually, by a robot or by a linear feeding mechanism, as seen in Fig. 5.13. Typically blanks are carried by suction cups to the furnace and once they are heated and taken out from the furnace, they are carried with "grip fingers" [18, 48, 49].

As soon as the blank leaves the furnace, it loses its heat to environment both by radiation and convection. It is well known that the blank loses more heat by radiation than by convection when its temperature is over 100 °C (212 °F), as shown in Fig. 5.14a. The earlier material handling systems did not have a heat shield, and thus the blank would lose more heat, Fig. 5.14b [52]. This was not a problem when the material was thick. However, recently thinner gage materials were also employed, and the temperature drop in thin blanks without heat shield is much higher than thin blanks [29].


**Fig. 5.13** Material handling systems: **a** manual handling [50], and **b** simple robot [18] are used for low volume production or tryouts; **c** industrial robot [51], and **d** linear feeders are used in mass production

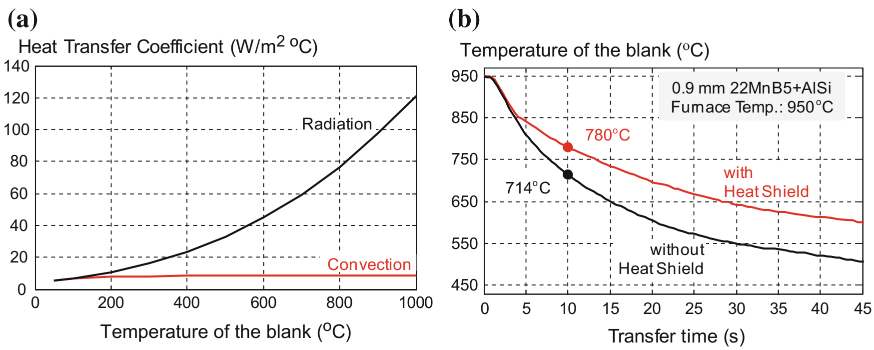



**Fig. 5.14** **a** Radiation versus convection of steel with respect to its temperature (recreated using the data from [53]), **b** a comparison of heat loss during blank transfer (recreated after [52]), **c** earlier material handling systems lacked the heat shield [49], **d** recent systems have heat shield to reduce heat loss due to radiation [12]

To reduce heat loss during transfer from furnace to the die, it is essential to reduce radiation by reflective heat shields. However, the last step of transfer (i.e, right before leaving the blank on lower die) cannot be done with a heat shield. To reduce the heat loss, heat shield is brought as close to the die as the transfer system allows, the final transfer is done by a fast double-bar system to reduce the time in air, Fig. 5.15.

One other method to increase the production in the press is to use more than one dies in the press. Hot stamping dies do not require high force/energy compared to cold


**Fig. 5.15** Material handling inside a heat shield as far as possible followed by handling with transfer feeder with two blanks at a time. The double-bar transfer system minimizes the time in open air

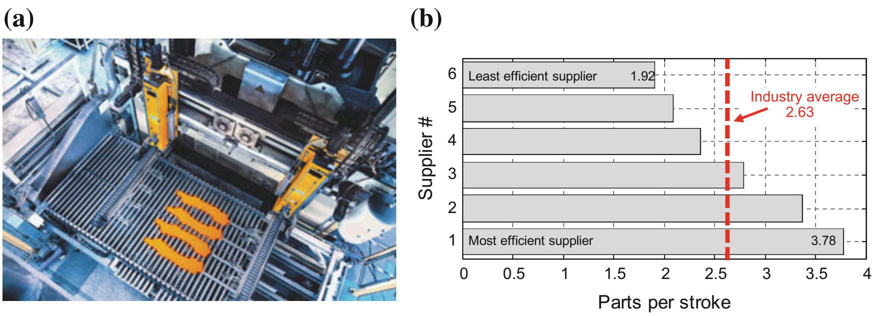



**Fig. 5.16** **a** Material handling system modified to have 4 parts per stroke [58], **b** Comparison of major hot stamping suppliers efficiency in 2011, measured by parts produced per stroke [57]

stamping of high strength steels. Therefore a typical 800 ton (8000 kN) press can form and quench more than one part. Material handling systems have to be updated to have the ability of transferring more than one blank at a time. Schuler has developed "PCH 4-out" where four blanks can be transferred and formed at one stroke, Fig. 5.16a. It is even possible to produce 8 parts per stroke using double-attached blanks (i.e., four blanks, but eight parts) [15]. Similarly, Amino and AP&T have designed automated lines with up to 8 parts per stroke (4 double-attached blanks) [54–56]. According to a study in 2011, global suppliers with over 10 million parts per year capacity had on average 2.63 parts per stroke, Fig. 5.16b [57]. It is important to notice that the difference between the so-called the "least efficient supplier" and the "most efficient supplier" is almost two-fold.

## 5.3 Hot Stamping Presses

In hot stamping applications, the press has to operate at five different conditions [37, 59]:

| | |
|---|---|
| **(1) Fast approach**: | almost no force, at high speed, |
| **(2) Forming**: | relatively low force requirement, at high speed, |
| **(3) Quenching**: | highest force requirement for a long dwell at the bottom dead center (BDC), |
| **(4) Fast return**: | almost no force, high speed, |
| **(5) Dwell at top**: | for material handling to remove the formed part and leave the next cycle's blank. |

Since there is a dwell at the (BDC), mechanical presses cannot be used. Typically, a conventional double-action hydraulic press or a single action hydraulic press with or without die cushion is used for hot stamping operations. The majority of the presses in hot stamping production worldwide are of the conventional hydraulic press with more or less developed technological solutions. In the next subsections, several types of presses that are already in mass production and those which are under R&D phase are examined in detail.

### *5.3.1 Direct Drive Hydraulic Press*

A direct drive hydraulic press uses pump(s) to deliver a certain volume flow ($\dot{Q}$), depending on the pump type and motor rpm ($\omega$). To speed up the press motion ($V$), more volume flow ($\dot{Q}$) is required. The press would generate force ($F$) only when there is a reaction force on the slide, such as forming load. Since hydraulic oil is compressible, to build up force, the oil column has to be compressed first. Thus, it takes some time to build up the force required. The power ($P$) required is the multiplication of force ($F$) and slide velocity ($v$) plus the mechanical and electrical losses [56, 60].

During fast approach, there is almost no force generated ($F = 0 \rightarrow P = Fv = 0$), so very low power is required. To reduce the cooling of the blank, the forming has to be done as fast as possible. Thus, during forming stage, high slide velocities in the order of 350–1000 mm/s (~800–2400 IPM) are desirable. Although forming forces are lower compared to cold forming, due to high slide velocity, forming is the most power requiring stage. During quenching—the longest portion of the cycle—the force is at maximum but the slide velocity is zero, resulting in almost no power consumption ($v = 0 \rightarrow P = Fv = 0$). While returning the slide to top dead center (TDC), the press has to carry the load of the slide and the upper die. To shorten the cycle time, return speed has to be as high as possible as well. The press would consume almost no power while waiting for the automation. An example power–time curve is shown in Fig. 5.17 [37, 56, 59–62].

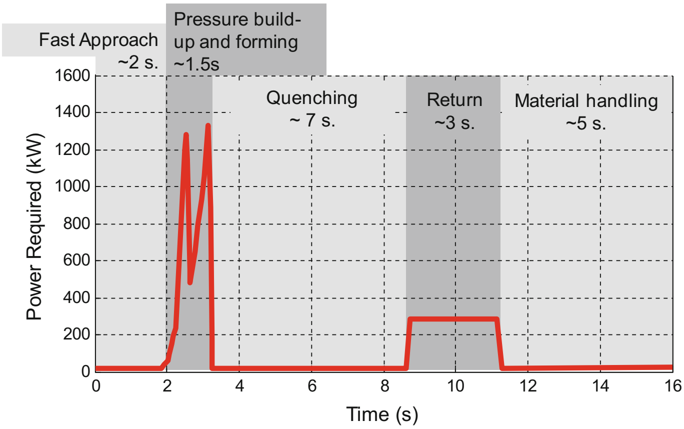



**Fig. 5.17** Power requirement of a 1,600 tons direct drive hydraulic press during an example hot stamping cycle (recreated after [37])

Direct drive hydraulic presses do not have an energy storage, so the power required during forming has to be pulled from the grid. As seen in Fig. 5.17, if a direct drive hydraulic press is to be used in hot stamping, very high installed power may be required. However, the press will only use the maximum power for a short portion of the cycle. To reduce the requirement of installed power, a smaller pump can be used with a hydraulic accumulator. When the press is idle, the pump fills the accumulator, and when high flow rate is required, the fluid is provided by the accumulator [59, 60].

## *5.3.2 Accumulator Drive Hydraulic Press*

A hydraulic accumulator has to be charged to its maximum pressure to ensure the availability of nominal press force during quenching at the bottom dead center [60]. At the beginning of the cycle, the pressure of the accumulator is applied to the piston, generating very high force, Fig. 5.18a [59]. Since there is no reaction on the slide, the slide accelerates quickly. An accumulator driven press is faster than a direct drive press. In a selected deep hot stamped part, Fig. 5.18b, the quenching time was 11 s, and depending on the hydraulic press drive the forming cycle was either 1 or 3 s. Considering the total time (12 s instead of 14 s) a $\sim$16% increase in output could be achieved by using an accumulator drive press [48]. The differences between the available force from the hydraulic accumulator system and the actual force required during forming the blank are waste of energy. Accumulator driven presses also have high maintenance costs due to complicated valve systems and additional hydraulic components [59, 60].

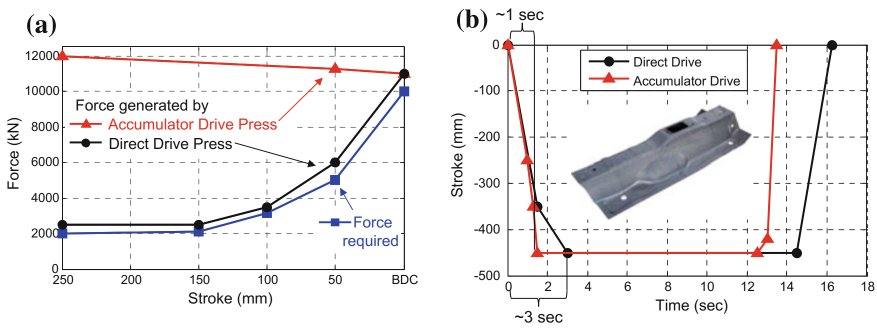



**Fig. 5.18** Comparison of direct drive and accumulator drive presses in terms of: **a** force generation in 1200 ton press (recreated after [59]), **b** cycle time of an actual product requiring high force over a long drawing distance (recreated after [48])

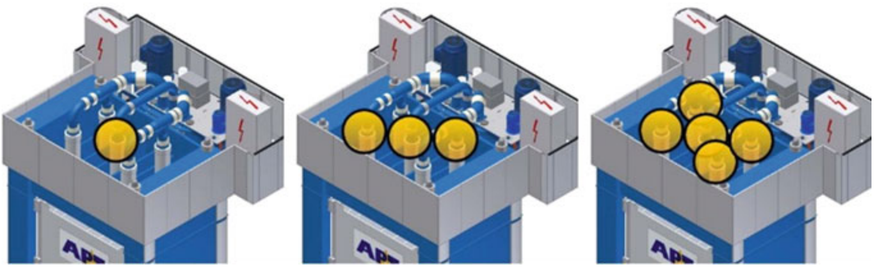


**Fig. 5.19** Hydraulic "gearbox" activating the five cylinders in steps following the actual need of press force

## *5.3.3 Multi-cylinder Hydraulic Press*

One method to save and utilize the energy in an efficient way is using multiple cylinders and activating them separately when needed, Fig. 5.19. For "low force–high speed", such as fast approach and return, only one cylinder is activated. When the force needed increases, the system activates other cylinders, at the expense of slide velocity. During quenching, all cylinders are activated to increase the contact pressure between the die and the formed part. Since all cylinders could be controlled separately, the system can compensate for some off-center load as well. The drive system could be direct or accumulator type [48].

## *5.3.4 Flywheel Hydraulic Press*

As discussed earlier, hydraulic accumulators are not energy efficient when they are not used at the maximum pressure. This also means that the efficiency of the press

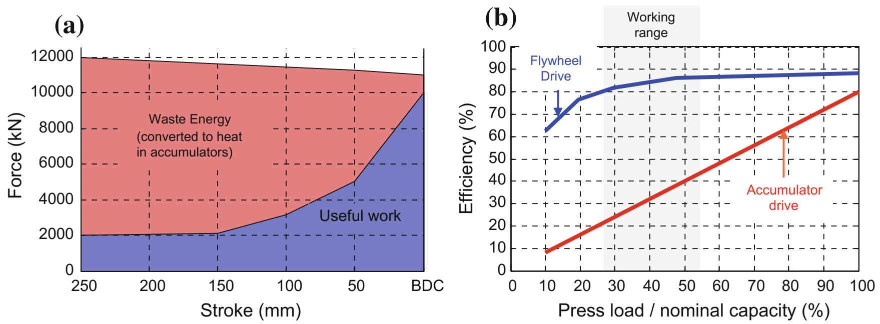



**Fig. 5.20** **a** Efficiency calculation for an accumulator drive press (modified from Fig. 5.18a), and **b** Energy efficiency of flywheel hydraulic presses compared with accumulator drive press (recreated after [49])

is lowered when it is used at lower forces than the nominal capacity. [59]. As shown in Fig. 5.20a, for this given example the total efficiency was approximately 30%. Storing energy in a flywheel, rather than a hydraulic accumulator has been proposed by Schnupp [37, 63] and Schuler [64] as an efficient way of reducing the installed power.

The presses from Schnupp are available from 600 to 1,600 tons capacity. The flywheel is directly mounted between the electric motor and the pump. A press may have up to three flywheel pump units and can be driven by one, two or three of them depending on the force/energy demand. The system is claimed to reduce the energy consumption and installed electric power. It has to be noted that, when the power required by the press is higher than the installed power (in case of preforming and forming), the flywheel will slow down and supply the energy. When the power required is less than the input (i.e., in quenching), the flywheels would speed up and store the excess energy [37, 63].

Schuler has also patented a similar flywheel driven hydraulic press design, specifically for hot stamping purposes. In this design, there is only one flywheel to which three pumps are mounted. Another (fourth) hydraulic pump is mounted on an electric motor and can charge the flywheel from return line, when needed. The system is said to be more efficient than a comparable accumulator drive especially at 30–50% of the nominal load, where most hot stamping "forming operations" are done, Fig. 5.20b. Schuler has named this system as "HED" High Efficiency Drive [59, 64].

### Multi-point Cushion System

In hot stamping dies, as explained in more detail in Chap. 6, blankholders and pads are typically used. These could be actuated by springs, gas cylinders or hydraulic cylinders installed in the die set. Another method of actuating (moving the die components and/or applying force on them) these die components is to use a cushion system which is a part of the press [65].

Cushion systems were originally developed for cold deep drawing operations. In a typical deep draw press, the blankholder sits on a number of cushion pins,

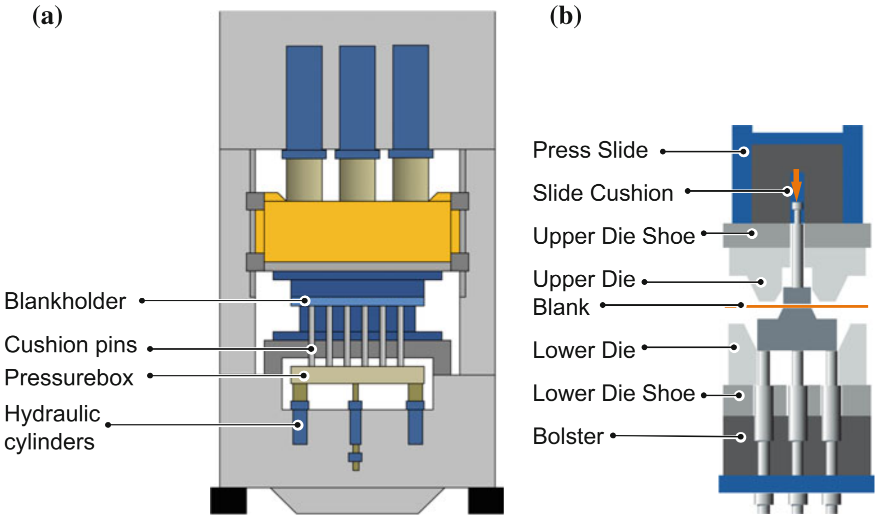



**Fig. 5.21** Cushion systems in hot stamping hydraulic presses: **a** hydraulic cushion with pressure box (recreated after [66]), **b** multi-point cushion system for hot stamping purposes [70]

which are actuated by the pressure box below the bolster plate. A conventional cushion system is shown in Fig. 5.21a. Due to elastic deflection in pressure box and possible variations in cushion pins' height, uniform blankholder pressure may not be sustained. In practice, die spotting and/or shimming is done to improve the uniformity of blankholder pressure [61, 66].

To control the blankholder pressure instead of a pressure box and cushion pins, a series of hydraulic cylinders may be used to apply force directly on the blankholder. According to Altan and Penter, multi-point cushion systems have already been developed as early as 1991 [67].

Schuler has developed a series of hydraulic presses with multi-point cushions in the slide and in the bed to maintain a uniform contact pressure. The presses equipped with this cushion systems are commercially named as PCH, Pressure Controlled Hardening [65, 68].

According to Aspacher [69], these presses have been around since 1990's. One of the earliest designs had four separate bed cushions and four separate cushions on the slide, each generating up to 300 ton force [65]. This design was replaced by a 23 pins in the bed and 10 pins in the slide [68]. The latest design now has 105 separate cushion pins, each can apply up to 315 kN force [70].

By using a number of cushion pins, each controlled separately, it is possible to compensate for: (1) thickness variation of the blank, (2) slide tilting, (3) die wear.

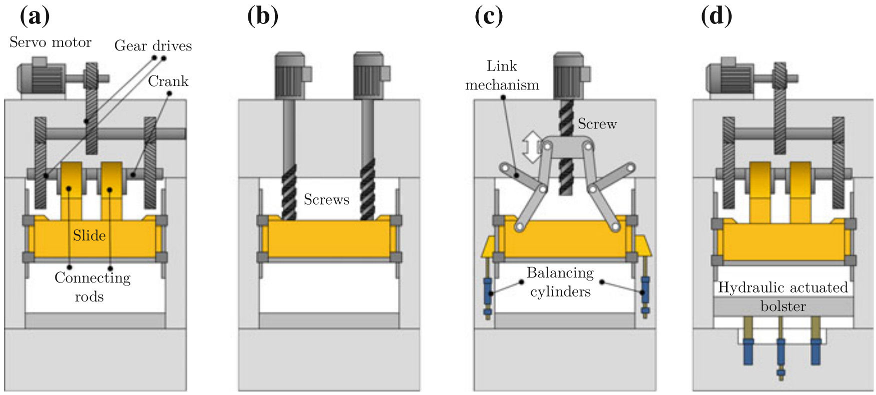



**Fig. 5.22** Servo presses for hot stamping: **a** Mechanical (crank-type) servo press, **b** spindle press (screw-type servo press), **c** mechanical link servo press, and **d** hybrid press with hydraulic actuated bolster (recreated after [56, 73–75])

## *5.3.5 Servo-Mechanical Press*

A servo-mechanical press is a press with crank, eccentric gear (Fig. 5.22a) or linkage drives (with or without ball screw, Fig. 5.22c) powered by a servo motor [71]. Theoretically, servo presses may have unlimited motion control and could be faster than hydraulic presses. Thus, they can complete a fast forming stage and can dwell at the bottom during quenching time. In practice however, servo-mechanical presses had two drawbacks for hot stamping processes [3, 56, 72, 73]:

(1) A servo-mechanical press is typically position (and speed) controlled, but not force. Unless a secondary control system is added, the force during quenching may not be constant due to dilatation/contraction of the tool and thinning of the blank due to forming.
(2) Restarting the press under load at BDC could damage the guides and bushings in crank or eccentric gear servo presses. A redesign in these components is advised for using servo-mechanical presses for long term in hot stamping.

Recently, several inventors and press makers have designed special servo mechanical hot stamping presses to address these problems.

Wood [74], for example, designed a hybrid hydraulic and servo-mechanical press, Fig. 5.22d. In this press, forming is done by the crank-slider mechanism of the top drive. Forming is completed when the slide is at the BDC. At this point the press may apply up to 200 tons force. During quenching, the bolster is actuated by hydraulic cylinders and may apply up to 1700 tons force. Although similar presses are known to be manufactured for cold stamping/coining operations [61], there is no information if such a press is being used in mass production hot stamping.

Japanese press maker Amino has already commercialized a servo press for hot stamping applications. A schematic (not exact representation) of this press is shown

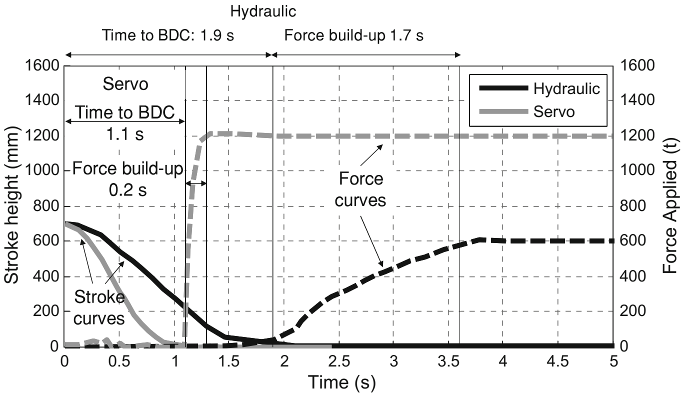



**Fig. 5.23** Comparison of hydraulic and servo-mechanic presses in stroke-time and force-time (recreated after [56])

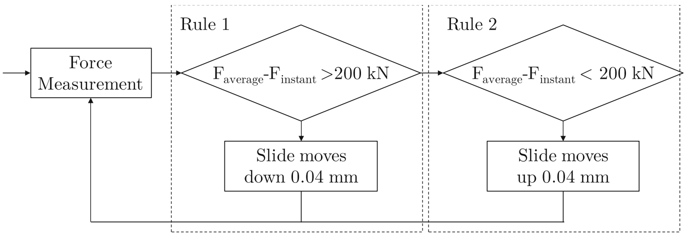



**Fig. 5.24** Block diagram of servo-press force control system (recreated after [72])

in Fig. 5.22c. The press is equipped with a force control system. If the instant load on the slide is ±7.5% out of the set value, the screw mechanism would adjust the position of the slide [56]. Maki et al., studied a 1200 ton servo press and found that it could generate the maximum force in almost 0.2 s. In comparison, a 600 ton hydraulic press took 1.7 s to build up its maximum force. This is because, in a hydraulic press, the oil column has to be compressed first. Servo press, as expected, also had an advantage in die close time (i.e., time to BDC). Details can be seen in Fig. 5.23 [56].

Wang et al. [72], at Huazhong University of Science and Technology, have designed a responsive control system for a 600 ton (6000 kN) servo-mechanical press [76]. A simple logic control with only two rules were applied, Fig. 5.24. The system allowed the servo press to apply a stable quenching force at the BDC.

Researchers at the Fraunhofer IWU, Chemnitz, used a spindle (screw-type servo) press as shown in Fig. 5.22b. The machine also had a servo cushion with screw system [75]. By synchronizing cushion and ram in a patented pulsation mode, the gap between the blankholder and die is changed with time. During deep drawing phase, the gap is increased instantly to lower the thinning and the strain around the punch radius. The wrinkles caused by high gap are flattened with a "return" stroke of

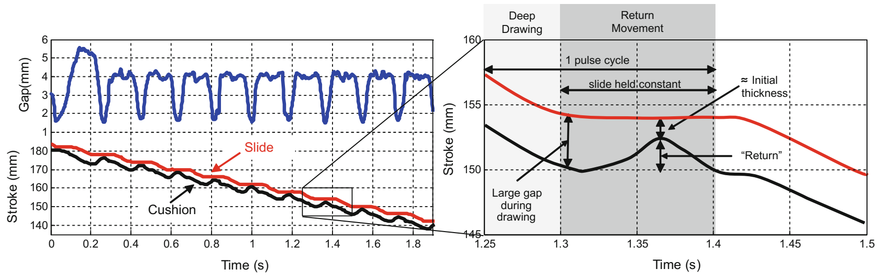



**Fig. 5.25** Stroke–time curve of the slide (ram) and cushion. The gap is controlled with time to facilitate drawing and to reduce the wrinkles (recreated after [75])

**Table 5.2** Maximum draw depth with cushion-ram pulsation [75]

| Process type | Slide speed (mm/s) | Max. Draw Depth (mm) with | | |
|---|---|---|---|---|
| | | 2 mm Gap | 3 mm Gap | 4 mm Gap |
| Conventional | 10 | 22 | 24 | 26 |
| Conventional | 200 | 24 | 25 | 26 |
| CRP | 10 | 25 | 46 | 46 |
| CRP | 200 | 24 | 46 | 46 |

the cushion, while the slide is held stationary, Fig. 5.25. By using this "cushion-ram pulsation" (CRP) method, deeper parts could be manufactured. Table 5.2 shows the improvement in draw depth with this system. Although a hydraulic press could also be programmed any stroke–time profile, a servo press can stop and move the cushion up and down much faster than a hydraulic press. Note that, in the particular example shown in Fig. 5.25, a total of 10 pulses are realized in less than 2.0 s.

Fagor has been developing servo presses for hot stamping since 2013. The first installation was done in 2015. Fagor chose to use the mechanical (eccentric gear-type) servo press for hot stamping (similar to Fig. 5.22a). To make the press capable of hot stamping, a number of modifications were done. These include a force control system, similar to the one described earlier in Fig. 5.24. In addition, since these presses were designed for long-term mass production, the connecting rod and bushing systems were modified to withstand the damages that may be caused by dwell at the BDC, Fig. 5.26. Another modification was a new system that would start the press at the BDC under load [73].

In a servo-mechanical press, as there is no hydraulic oil and risk of leakage, fire risks are reduced [3]. By using energy recovery mode, a servo press can generate electricity while it is slowing down. For comparison purposes, an example hot stamping cycle was run in a hydraulic press and a servo press. As seen in Fig. 5.27, servo press not only improves the cycle time by almost 1 s, but also saves ∼35% energy [73].

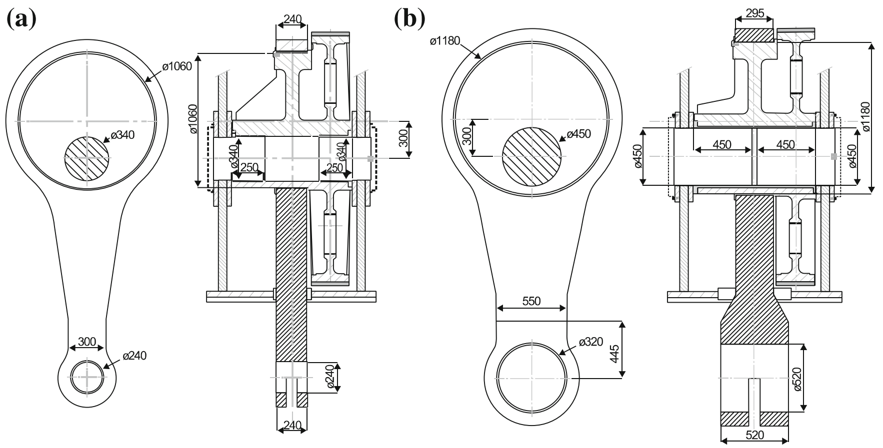
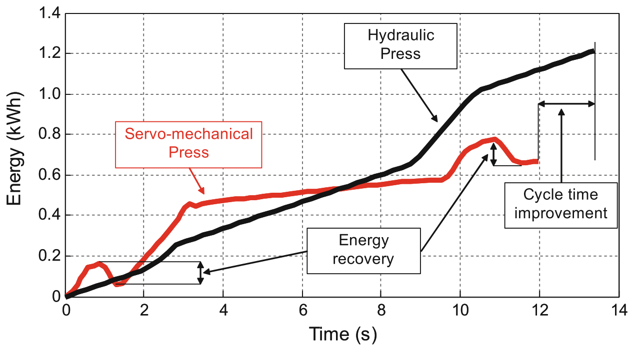



**Fig. 5.26** Connecting rod and bushing design of **a** typical servo-mechanical press, **b** servo-mechanical press designed for hot stamping [73]




| Hot stamping cycle | |
|---|---|
| Total Stroke | 950 mm |
| Drawing Stroke | 300 mm |
| Drawing Force | 4,000 kN |
| Quenching Force | 10,000 kN |
| Quenching Time | 6 sec. |

**Fig. 5.27** Comparison of cycle time and energy consumptions of servo-mechanical and hydraulic presses (re-created after [73] with additional information from A. Ormaetxea)

## 5.4 Hot Stamping Lines by Capacity

The automotive industry has to offer more variants of cars, in much shorter development times and for shorter production periods, compared to a few decades ago. For example, BMW had only five different models in 1980 (3, 5, 6, 7 series and M1), whereas in 2015, there were 22 different BMW series [77]. Although car makers are taking advantage of part and platform commonality to reduce the number of different parts to be produced, still in the upper body a number of "exclusive to variant" parts have to be produced [78]. For these reasons, there is a demand for at least two types of lines: (1) small volume production lines for model exclusive parts, and (2) mass production lines for platform parts and/or high volume cars [52].

The Spanish press maker Loire Safe (later acquired by Gestamp and renamed as Loire Gestamp), introduced three tailored lines in 2011: Large, Medium and Small lines. In the small line a low die height 630 ton press was used, whereas the medium and large lines have larger presses and longer furnaces. The large line is also offered with a moving bolster to speed-up die changing [79, 80].

Similarly, German press maker Schuler also offers at least two different press hardening lines. In the PCH Hardline, a 600 ton press with 3.0 m × 1.2 m table is offered. The press has 23 cushion pins in the bolster, generating a total of 300 ton force. Additional 10 pins are installed in the slide to apply 250 ton force. The furnace length is limited to 20 m (65 ft). The line is optimized for 8–15 s cycle time and may be offered with a tandem die change cart system. The standard version is optimized for 1–2 parts/stroke. For higher production volume, Hardline Pro is offered. In this version, the press is a 1200 ton, with an array of 105 cushion pins. This version has a T-track bolster system for quick die change, and is offered with a 25 m (82 ft) long furnace and can produce up to four parts per stroke. Last, there is a Hardline twin, very similar to Hardline Pro in terms of dimensions but has two separate slides, each can apply 600 ton force. The slides could be synchronized or used separately. This version is offered with 60 m (197 ft) long furnace [59, 64, 70].

A recent development by Schnupp presses in collaboration with Neue Materialen Bayreuth is a vertical hot stamping line for small parts production. In this line, a contact-type heater is installed over a horizontal hydraulic press with 50 ton capacity, as shown in Fig. 5.28. Once the blank is austenitized the contact plates open, and the heated blank is moved very quickly to the hydraulic press with the help of gravity. The system can form thin materials (0.5–0.8 mm) and requires only 4–5 m$^2$ (∼43–54 sq.ft) floor space. A working prototype has been introduced in EuroBlech 2016 [81–83].

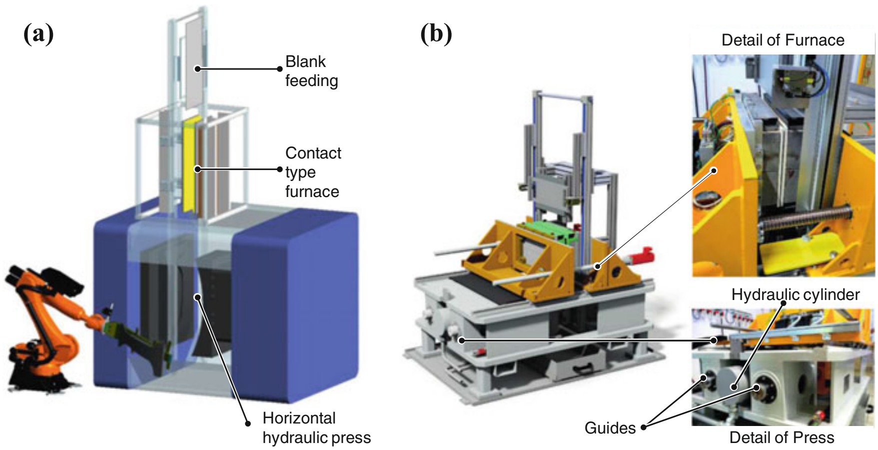



**Fig. 5.28** Vertical press hardening line, "VertPress": **a** concept (recreated after [81]), and **b** photo of the system with details [82])

## References


1. K. Eriksson, Bringing it together. Presented at AP&T Press Hardening, Next Step Seminar, Novi, MI (2010). Accessed 15 Sep 2010
2. H. Karbasian, A.E. Tekkaya, A review on hot stamping. J. Mater. Process. Technol. **210**(15), 2103–2118 (2010)
3. E. Gamboa, X. Agirretxe, J.M. Martin, K. Gorostiza, Compact line conception for hot forming lines, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 181–187
4. P. Siebert, M. Alsmann, H.J. Watermeier, Influence of different heating technologies on the coating properties of hot-dip aluminized 22MnB5, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 457–464
5. H. Lehmann, Developments in the field of schwartz heat treatment furnaces for press hardening industry, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 171–179
6. F.J. Ebner, Hotphase - press hardening automotive solutions by EBNER, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 247–253
7. H. Lehmann, Furnaces for press hardening. Presented at AP&T Press Hardening, Next Step Seminar, March 24, Shanghai, China (2010)
8. H. Lehmann, Roller hearth furnaces for hot-form hardening. IDDRG Graz Austria **2010**, 131–140 (2010)
9. Volkswagen Media Services, http://www.volkswagen-media-services.com
10. V. Uthaisangsuk, Hot stamping of ultra high strength steel: a key technology for lightweight automotive design. Presented Automotive Summit 2014, June 19–20, Bangkok, Thailand (2014)
11. Schuler. Hot forming systems: light-weight in volume production. Product catalogue (2006)
12. Audi Media Services, http://www.audi-mediaservices.com
13. M. Kahl, Some like it hot. *Automotive Manufacturing Solutions* (2004), pp. 49–52
14. B.A. Behrens, S. Hübner, Conductive heating in press-hardening process. Presented at Doors and Closures in Car Body Engineering 2011, November 16–17, Bad Nauheim, Germany (2011)
15. Schuler. Private communication (2013)
16. P. Hu, L. Ying, B. He, *Hot Stamping Technology and the Main Equipment* (Springer, Singapore, 2017), pp. 19–44
17. M.J. Holzweissig, J. Lackmann, S. Konrad, M. Schaper, T. Niendorf, Influence of short austenitization treatments on the mechanical properties of low-alloy steels for hot forming applications. Metall. Mater. Trans. A **46**(7), 3199–3207 (2015). Jul
18. V. Ploshikhin, A. Prihodovsky, J. Kaiser, R. Bisping, H. Lindner, C. Lengsdorf, K. Roll, New heating technology for the furnace-free press hardening process, in *Proceedings of TTP 2011* (2011)
19. J.N. Rasera, Development of a novel technology for rapidly austenitizing usibor 1500p steel (2015)
20. 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. *CIRP Annals - Manufacturing Technology* (2017)
21. M. Reinstettel, The door sidecrash beam ın the new BMW i8: application of a press hardened 7xxx aluminium alloy panel, in *Proceedings of 5th International Conference on Accuracy in Forming Technology (ICAFT 2015)* (2015), pp. 349–356
22. R. Kolleck, R. Veit, M. Merklein, J. Lechler, M. Geiger, Investigation on induction heating for hot stamping of boron alloyed steels. CIRP Ann. - Manuf. Technol. **58**(1), 275–278 (2009)
23. M. Uslu, Docol 22mnb5 Çeliğinin balistik Özelliklerinin İncelenmesi (investigation of ballistic proerties of docol 22mnb5 steel - in turkish) (2007)
24. K. Mori, S. Maki, Y. Tanaka, Warm and hot stamping of ultra high tensile strength steel sheets using resistance heating. CIRP Ann. - Manuf. Technol. **54**(1), 209–212 (2005)

25. C.W. Lee, W.S. Choi, Y.R. Cho, B.C.D. Cooman, Microstructure evolution of a 55 wt. hardening steel during rapid heating. Surf. Coat. Technol. **281**, 35–43 (2015)
26. B.A. Behrens, S. Hübner, S. Schrödter, J. Uhe, Conductive heating opens up various new opportunitites in hot stamping, in *Proceedings of 5th International Conference on Accuracy in Forming Technology (ICAFT 2015)* (2015), pp. 157–174
27. W. Liang, L. Wang, Y. Liu, Y. Wang, Y. Zhang, Hot stamping parts with tailored properties by local resistance heating. Procedia Eng. **81**, 1731–1736 (2014); 11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014, Nagoya Congress Center, Nagoya, Japan
28. W. Liang, Y. Liu, B. Zhu, M. Zhou, Y. Zhang, Conduction heating of boron alloyed steel in application for hot stamping. Int. J. Precis. Eng. Manuf. **16**(9), 1983–1992 (2015). Aug
29. K. Steinhoff, Retaining control of complexity - the real challenge in contemporary hot stamping, in *4th International Seminar on Hot Sheet Metal Forming Technology* (2016), pp. 9–40
30. C. Lobbe, O. Hering, L. Hiegemann, A.E. Tekkaya, Setting mechanical properties of high strength steels for rapid hot forming processes. Materials **9**(4), 25 (2016)
31. T. Senuma, Y. Takemoto, Effect of rapid heating on evolution of microstructures and coating layers in hot stamping processes, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 465–472
32. M. Terziakın, Instant heating process with electric current application to the workpiece for high strength metal forming, US Patent 6,463,779 (2002)
33. K. Ishiguro, M. Furuhashi, Hot press forming apparatus and hot press forming method, US Patent 9,206,488 (2015)
34. A. Mikuni, T. Sagisaka, T. Shiga, The new lexus is. Presented at EuroCarBody 2013, September 25–26, Bad Nauheim, Germany (2013)
35. R. Kolleck, W. Weiß, P. Mikoleizik, Cooling of tools for hot stamping applications. IDDRG Graz Austria **2010**, 111–119 (2010)
36. H. Schülbe, M. Jestremski, B. Nacke, Induction heat treatment for press hardening process, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 481–488
37. R. Hund, M. Braun, Continuous improvement of hot forming technology, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 189–200
38. J.J. Coryell, P.J. Belanger, Pre-diffused Al-Si coatings for use in rapid induction heating of press-hardened steel, US Patent 9,677,145 (2017). Accessed 13 June 2017
39. S. Aikawa, Far infrared heating furnace for steel plate for hot pressing, US Patent 9,677,145 (2017)
40. S.K. Chaudhury, D. Apelian, Fluidized-bed: high efficiency heat treatment of aluminum castings. Heat Treat. Prog. **7**(6), 29 (2007)
41. T. Marten, T. Troster, S. Adelbert, A. Kadim, Fluidized bed heating of blanks for the hot forming process, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 473–480
42. R. Neugebauer, R. Müller, A. Bester, Innovative concept for combining the austinitization and surface coating of steel into one step. Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf. **226**(7), 1281–1284 (2012)
43. T. Kurz, New developments in zinc coated steel for press hardening. Presented at Insight Edition Conference, September 20–21, Gothenburg, Sweden (2011)
44. J. Watkins, Material development. Presented at AP&T Press Hardening, Next Step Seminar, Novi, MI (2011)
45. R. Aldén, Metallurgical investigation in weldability of aluminium silicon coated boron steel with different coating thickness. *Bahcelor Degree Thesis, KTH Royal Institute of Technology, Stockholm, Sweden* (2015)
46. M. Windmann, A. Röttger, W. Theisen, Formation of intermetallic phases in Al-coated hot-stamped 22MnB5 sheets in terms of coating thickness and Si content. Surf. Coat. Technol. **246**, 17–25 (2014)

47. S. Fujita, S.J. Maki, H.I. Yamanaka, M. Kurosak, Corrosion resistance after hot stamping of 22MnB5 steels aluminized with 80g/m2 c.w. and ZnO coating, in *5th International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Toronto, ON, Canada* (2015), pp. 681–690
48. J. Karlsson, Press requirements. Presented at AP&T Press Hardening, Next Step Seminar, Novi, MI (2010). Accessed 15 Sept 2010
49. Schuler Inc. Press hardening with pch (2008)
50. voestalpine Media services, http://www.voestalpine.com/group/en/press
51. L.A. Kren, Specialty hydraulic press. Metal Forming Magazine (2015), pp. 20–23
52. M. Skrikerud, Next generation of compact hot forming lines for optimised throughput with different materials. Presented at Forming in Car Body Engineering 2014, September 24–25, Bad Nauheim, Germany (2014)
53. A. Shapiro, Finite element modeling of hot stamping. Steel Res. Int. **80**(9), 658–664 (2009)
54. Schuler. PCH 4-out. *Newsletter Special Edition - PCH Technology* (2010)
55. P. Josefsson, General outlook - the future for press hardening in the automotive industry. Presented at AP&T Press Hardening, Next Step Seminar, September 19th, Dearborn, MI, USA (2012)
56. T. Maki, M. Amino, K. Hirano, H. Murai, Mechanical link servo press for hotforming, in *5th International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Toronto, ON, Canada* (2015), pp. 179–187
57. P. Belanger, *The Future for Press Hardening in the Automotive Industry*. Presented at AP&T Press Hardening, Next Step Seminar, Novi, MI (2011), p. 2011
58. P. Thom, From first draft to serial production: increase ROI with turnkey hot stamping solutions. Presented at Grundig-Akademie 4th PHS Suppliers Forum (2016). Accessed 22 Sept 2016
59. E. Lundström, Hot stamping press technology. Presented at Schuler Hot Stamping Workshop, May 14, Dearborn, MI, USA (2013)
60. E. Billur, Hydraulic presses, in *Sheet Metal Forming - Fundamentals*, ed. by T. Altan, A.E. Tekkaya (ASM International, 2012), pp. 181–201
61. Schuler GmbH, *Metal Forming Handbook* (Springer Science & Business Media, 1998)
62. A. Kirk, J. Neil, Selecting a hydraulic hot-stamping press. Stamp. J. 22–27 (2014)
63. ThyssenKrupp Steel Europe. Private communication (2013)
64. Schuler Pressen GmbH. Press hardening with PCH Flex –fast, flexible, cost-effective. Product/Service Brochure (2014)
65. J. Aspacher, Press hardening - “dead end” or “take off”. Presented at 25th European Car Body Conference, March 13–14, Bad Nauheim, Germany (2007)
66. T. Altan, A. Erman Tekkaya, *Sheet Metal Forming: Processes and Applications* (ASM International, 2012)
67. T. Altan, L. Penter, Application of modern cushion systems to improve quality and productivity in sheet metal forming, in *Proceedings of the CIRP Conference Machine-Process Interactions, Vancouver* (2010)
68. J. Aspacher, Hydraulic presses in use for light weight production in the automotive industry. Presented at Forming in Car Body Engineering 2011, September 27th, Bad Nauheim, Germany (2011)
69. 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)
70. R. Vollmer, C. Palm, Improving the quality of hot stamping parts with innovative press technology and inline process control, in *IDDRG 2017, Munich, Germany* (2017)
71. E. Billur, B. Çetin, M.M. Yılmaz, A. G. Oğuz, A. Atay, K. Ersoy, R.O. Uğuz, B. Kaftanoğlu, Forming of new generation AHSS using servo presses, in *5th International Conference on Accuracy in Forming Technologies, Chemnitz, Germany* (2015), pp. 175–191
72. L. Wang, B. Zhu, Y. Zhang, Y. Wang, X. An, Q. Wang, A smart process control strategy for press hardening production, in *6th International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Atlanta, GA, USA* (2017), pp. 515–524

73. A. Ormaetxea, G. Ibañez, Servomechanical press makes foray into hot stamping. Stamp. J. 18–21 (2015)
74. C. Wood, Hot forming press, U.S. Patent App. 14/240,174 (2012). Accessed 22 Aug 2012
75. Dirk Landgrebe, Anja Rautenstrauch, Andreas Kunke, Stefan Polster, Sebastian Kriechenbauer, Reinhard Mauermann, The effect of cushion-ram pulsation on hot stamping. AIP Conf. Proc. **1769**(1), 070014 (2016)
76. J. Meng, L. Wang, Q. Wang, Y. Sun, Y. Zhang, Research on the model of the production of hot forming process and the optimization method of production cycle, in *5th International Conference on Advanced Design and Manufacturing Engineering (ICADME 2015)* (2015), pp. 1949–1952
77. F. Schieck, Energy and resource-efficient process routes in hot sheet metal forming. Presented at Forming in Car Body Engineering 2015, September 29–30, Bad Nauheim, Germany (2015)
78. S. Behm, The Honda Ridgeline. Presented at Great Designs in Steel 2017 (2017)
79. J.M. Berasategi, C. Garbalena, B. Irazu, G. Gonzalez, Past and future for taylor-made hot stamping lines, in *3rd International Conference on Hot Sheet Metal Forming of High Performance Steel, CHS2, Kassel, Germany* (2011), pp. 255–261
80. 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
81. Bundesministerium für Bildung und Forschung, (German Federal Ministry of Education and Research). KMU-innovativ Forschung für die Produktion von morgen (SME-innovative “Research for the production of tomorrow”) (2014)
82. Schnupp Gmbh & Co. Hydraulik KG. Vertpress. kompaktpresse für die warmumformung. Product Catalogue (2016)
83. Neue Materialien Bayreuth GmbH, Warmumformung auf kleinstem Raum: NMB präsentiert neuen Anlagenprototypen (hot forming in the smallest space: NMB presents new plant prototypes). Press Release (2016)