Chapter 2
Hot Stamping Technology and the Main Equipment

2.1 The Hot Stamping Technology of High Strength Steel

2.1.1 Brief Introduction of Hot Stamping Technology

In recent years, automotive lightweight has led to the increasing demand of high strength steel (HSS) auto parts. Lots of correlative companies and research institutes in America, Europe, Japan, and China have invested large amount of energy into the research of advanced automotive HSS forming technology. Though the advantage of HSS is high strength, it still has some disadvantages such as the poor forming performance, the uncontrollable springback, and easy to crack during forming process. Therefore, it is difficult to realize the manufacture of complex auto parts by adopting traditional cold stamping technology, where the hot stamping technology is needed.

HSS hot stamping technology is a new manufacturing technology developing in recent years, which combines the traditional hot forging and cold stamping technology. It is a mode of production that integrates the stamping of steel under the condition of high temperature and forming and quenching in dies. It is also known as Hot Forming, Hot Stamping, Hot Press, Press Hardening, or Die Quenching [51] abroad. As early as in the middle of the last century, the HSS hot stamping technology research had appeared in aviation and nuclear industry, such as the United States NASA. Norrbottens Jernverk exploited the hot stamping technology in 1973, which was suitable for automobile parts manufacturing. Volvo Car Company did research on the applicability of hot stamping parts in one type of its cars, and since 2000, more hot stamping parts were used in automobile body manufacturing. The total quantity had reached more than 100 million in 2007. It was from 1990s that the world's largest steelmaker, Arcelor Mittal company, began to make a study of hot stamping technology industrialization and developed the famous Al–Si coating hot stamping steel USIBOR1500 and retrofit 1500p series [21, 39, 42]. At present,

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the HSS hot stamping technology has become a hot topic which many car manufacturers pay attention to around the world [45].

As shown in Fig. 2.1, hot stamping technology of HSS can be used to manufacture car structural components whose tensile strength is up to 1500 Mpa, such as the front bumper, tail bumper, A column, B column, C column, roof frame, floor frame, door panel, door anti-beam, and so on [35, 57]. The new China automotive lightweight technology innovation union work conference, held in Shanghai in May 2013, pointed out that China's auto market maintained steady growth in 2012, and the average monthly production and sales were totally more than 1.5 million vehicles. Annual cumulative production and sales were more than 19.2718 million vehicles. Hot stamping parts, as a necessary choice of advanced bodywork, have become a specification. New models, especially SUV and b-class more luxury cars, gradually raised in the market share, which has huge demand for hot stamping parts, and the market demand of hot stamping production equipment and production lines also arise at the historic moment.

According to the related information of EuroCarbody from 2008 to 2012 [55], represented by Audi, international auto giants had used hot stamping parts as a mainstream configuration of lightweight body structure and security design, which were applied widely in the automobile body design and manufacturing. The use ratio of hot stamping parts around the world auto enterprises had greatly increased from 4–15 to 10–30 %: the number of hot stamping parts used in advanced cars in Land Rover and Audi had reached or was close to 25, and the proportion accounted for more than 20 % of the total number of body in white; FIAT plans to use hot stamping parts in the subsequent models, and the proportion is more than 16 %; there are about 6–10 % usage rate of hot stamping parts in Ford and Daimler-Chrysler's. There are totally 165 body parts on the first five-star collision protection utility vehicle, Ford wind star, while nearly 100 of the parts are made with hot stamping of HSS and the proportion is more than 60 %; the usage ratio of hot stamping of boron steel in VOLVO cars has gradually risen from 7 % of XC90

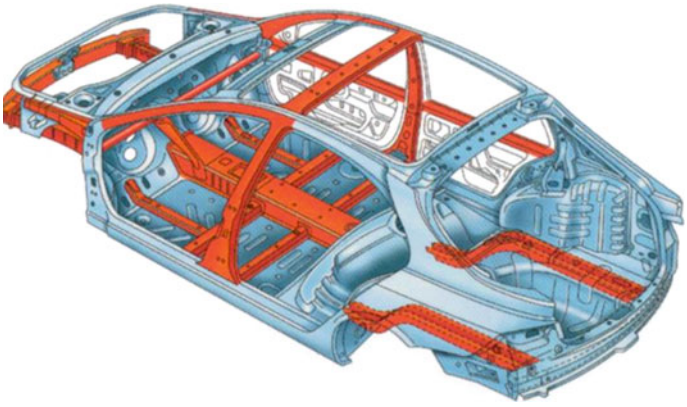


Fig. 2.1 Applications of hot stamping parts in auto BIW

models to 17 % of the S60 series, which is expected to reach 45 % of the total body in white in the future, as shown in Fig. 2.2.

Along with the integration of Chinese automobile manufactures and the international auto industries, the application of hot stamping products will be gradually improved among domestic automobile manufacturers [13, 50]. Hot stamping products are used widely in body structure, which will enhance the safety of the car and greatly promote lightweight prospects of Chinese independent automobile brands. In order to improve their product's competitive advantage within the industry both at domestic and overseas market and strengthen the lightweight and safety performance of the models, many auto private enterprises, such as Great wall, Geely, Changan, Chery, etc., are actively seeking superior cost-effective hot stamping parts suppliers and opportunities, so that it will be the trend of future development to apply hot stamping auto parts widely in automobile body manufacturing.

2.1.2 Hot Stamping Process

Hot stamping process is the necessary means to realize the product forming and strength increasing of hot stamping steel, and it is the indispensable premise for HSS of hot stamping to acquire high strength performance. Its typical technological process is: first, heat the sheet to a specific temperature range for austenization and austenitize it completely, and then transfer it into the water cooling hot stamping dies for stamping and quenching, and finally realize the microstructure's phase transformation and the increase of strength. According to the complexity of

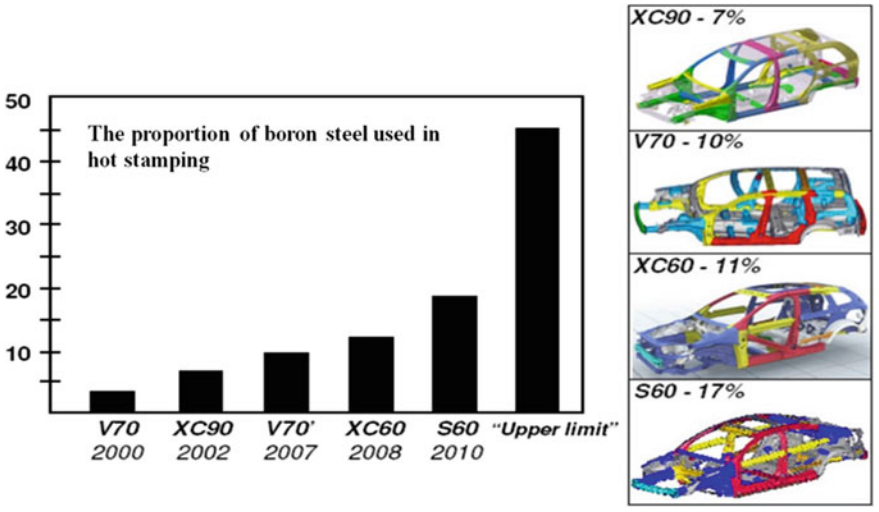


Fig. 2.2 The proportion of hot stamping boron steel applied in VOLVO vehicles

processing and the forming process of actual parts, hot stamping process can be divided into directly hot stamping and indirectly hot stamping process.

1. Direct hot stamping process

In the direct hot stamping process, a blank is heated up in a furnace, transferred to the press and subsequently formed and quenched in the closed dies [6, 10, 19, 29]. As shown in Fig. 2.3, the steel plate is first uncoiled and cut according to the shape of the product, and then the blank is transferred to a continuos furnace, in which it is heated and fully austenitized. Thus, the product is formed and quenched after the blank is transferred to the hot stamping dies with cooling system. Afterwards, the product is trimmed by laser and finished through other follow-up processes.

The advantages of direct hot stamping process are as follows:

(1) The blank is formed and hardened in one mold, which saves the cost of preforming and accelerates the pace of production.
(2) The blank is flat, which not only saves heating area and energy, but also can be heated by a variety of heating methods, for example, induction heating.

The disadvantages of hot stamping process are as follows: it cannot be used for forming automobile parts with complex shapes, and it needs the laser cutting equipment. In addition, the design of cooling system of molds is more complex.

For automotive body structure, the parts with simple shape, not necessary for deep drawing, can be manufactured by the direct hot stamping, such as the inside and outside pieces of b-pillar, the inner plate of side panels, the inner plate of the threshold, the central pillar of front bezel and door beam, and so on (Fig. 2.4) [19, 40].

Figure 2.5 shows the hot stamping tools for an automobile front fender center pillar and the forming process. The shape of this center pillar is simple and the drawing depth is small, so it can be manufactured by the direct hot stamping process. Put the original blank into furnace, heat to 950 °C and fully austenitize for 5 min, then quickly transferred it into the water cooling hot stamping tools (Fig. 3.3) to form it and quench it. The finally obtained hot stamping parts are shown in Fig. 2.6. In order to verify the feasibility of forming process, the microstructure and the mechanical properties for hot stamping parts were tested.

Six typical test samples in different regions of the center pillar are selected for hardness measurement and metallographic observation, as shown in Fig. 2.7. From the hardness results shown in Table 2.1, it can be found that all the samples' hardness (HR) are higher than 47, far more than that of the original steel, which

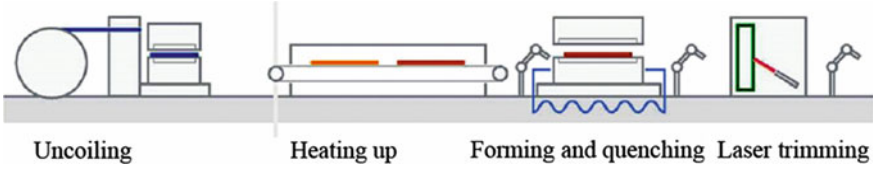


Fig. 2.3 Sketch map of direct hot stamping process



Fig. 2.4 Parts with the direct method of hot stamping

Fig. 2.5 Hot stamping die of brace dase panel, CTR and its process

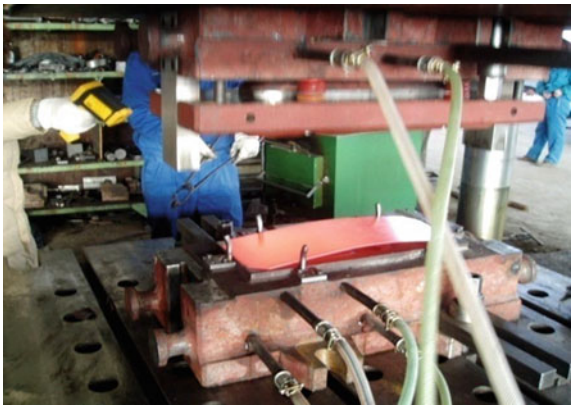


Fig. 2.6 Brace dase panel, CTR with one-step method of hot stamping



indicates a microstructure transformation in the steel part during hot stamping process. The metallographic results illustrated in Fig. 2.8 shows that the microstructure of original steel is mainly mixture of ferritic and pearlitic, together

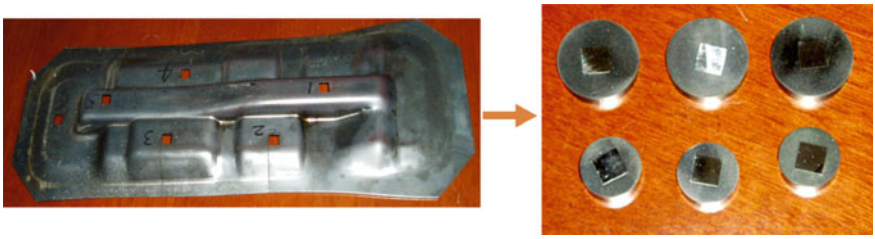


Fig. 2.7 Testing samples for microstructure and hardness of the hot stamping part

Table 2.1 Distribution of rockwell hardness (HRC)

Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
47	48.2	49.8	49.5	50	48.7

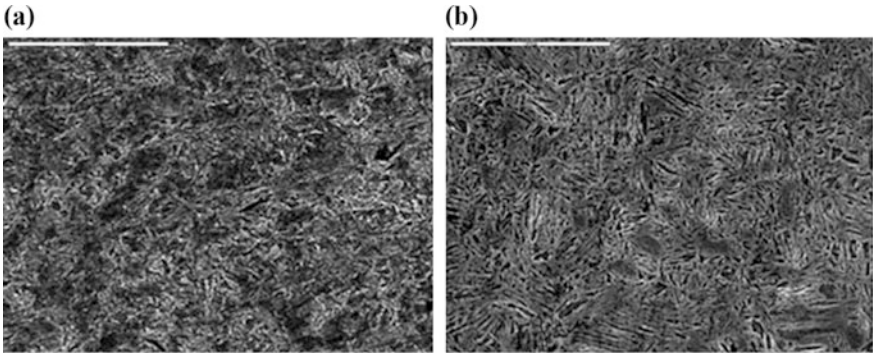


Fig. 2.8 Microstructure of the material before hot stamping and after hot stamping. **a** Microstructure of the raw material. **b** Microstructure of the hot forming product

with a bit of carbide. While the microstructure of steel after hot stamping is the uniform martensite, which has a martensite content of more than 95 %.

The hot stamping steel's engineering stress–strain curve obtained by tensile test is shown in Fig. 2.9, from which we know that the yield and tensile strength of hot stamping steel exceed 1000 and 1600 MPa, respectively. All the results illustrated above declare that the properties of the central pillar produced by direct hot stamping can meet the technical requirements of hot stamping [26, 41]. And it also declares the feasibility of the above direct stamping process.

2. Indirect hot stamping process

In the indirect hot stamping process, the sheet metal is preformed by cold forming before it is heated to austenite temperature in a furnace. After being held for a period of time for full austenization, it will be transferred into the hot stamping tools with cooling system to be stamped and quenched at the same time [29]. The indirect

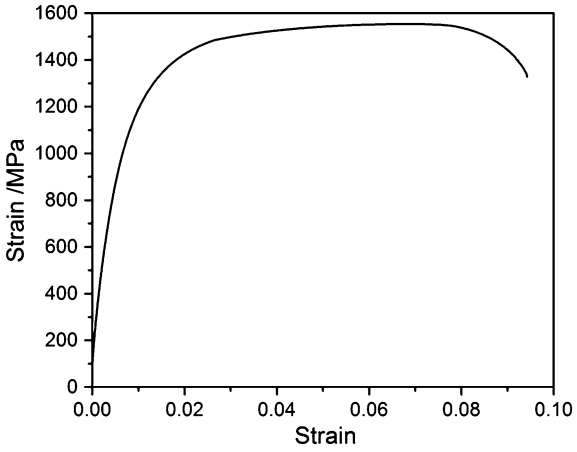


Fig. 2.9 Engineering stress–strain curve of the front fender center pillar

hot stamping process is also named as "multi-step" hot stamping as shown in Fig. 2.10. Compared to the cold stamping steel, though the flowability of the heated steel increases, the tensile strength would decrease accordingly, making it easy to crack for complex part during forming process. The indirect hot stamping process is the exact method invented to solve the problem and form complex auto parts that may not be formed by the direct hot stamping process.

Compared to the direct hot stamping, the HSS sheet is uncoiled and cut according to the shape of the product, then preformed by the traditional process such as cold forming process, flanging, punching and cutting-edge, and so on. After that, the preformed semi-finished product is transferred to the continuous furnace to be heated and insulated before it is sent to be formed and quenched. Afterwards the product will be trimmed by laser processing or other necessary follow-up processes according to the characteristics of the components, or directly output finished product.

For automotive body structure, the parts that have complex shape or need deep drawing or punching, trimming or other complex technology must be manufactured by the indirect hot stamping process, such as the inside and outside pieces of B-pillar, the inner plate of side panels, the central pillar of front fender and door beam, etc. (Fig. 2.11).

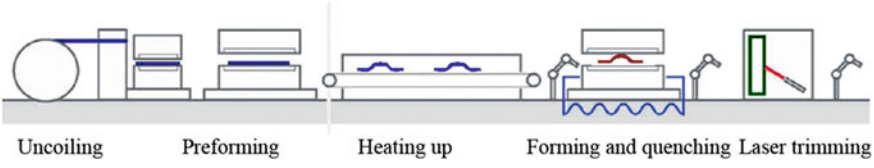


Fig. 2.10 Sketch map of hot stamping process with indirect method of hot stamping

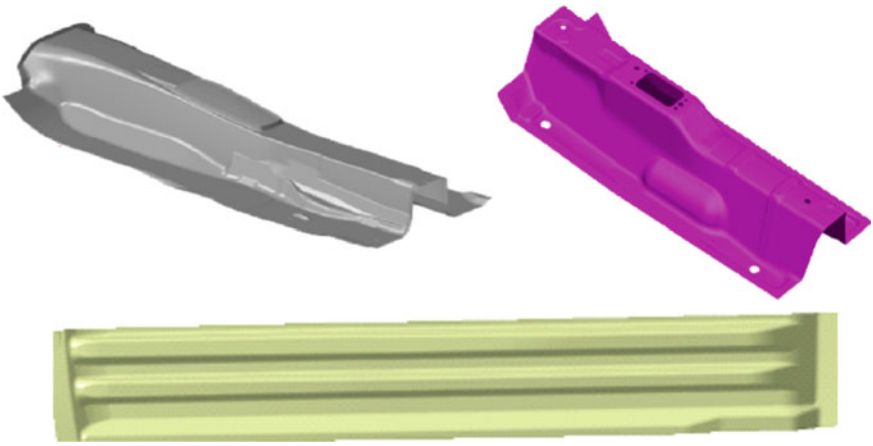


Fig. 2.11 Parts produced by indirect hot stamping technique

The advantages of indirect hot stamping process are as follows:

(1) The parts with complex shapes and almost all of the current stamped carrying parts can be formed by indirect hot stamping process.
(2) After the preforming of the blank, it is unnecessary to worry about the forming performance of the blank at high temperature in subsequent hot stamping process, which can ensure the martensite microstructure of the blank followed by complete quenching.
(3) The blank can be processed by trimming, flanging, punching and other processing after being preformed so that it will be easier for processing after it is quenched. For example, the blank that is quenched must be trimmed by laser cutting equipment, which greatly increases the cost.

The enforced beam shown in Fig. 2.11 is applied to the hot stamping experiment. First, the direct hot stamping process is used and the formed part is shown in Fig. 2.12. It is obvious to find that the cracks happened at both ends of the beam. This is due to the fact that the enhanced beam has three U-shaped deep drawing areas, which greatly increase the difficulty of forming. Aimed at this kind of beam, the indirect hot stamping process is developed based on the numerical simulation [11] and two sets of dies are used to form the enhanced beam. The preforming die is shown in Fig. 2.13a and the dies for quenching, the productive process and the final formed product are illustrated in Fig. 2.13b.

First, according to the shape of the part, the blank size is got in software by inverse forming algorithm before the blank is uncoiled and cut, and then the blank is sent into the preforming dies, as shown in Fig. 2.13a. The required geometry of the part is obtained by trimming process after being formed by the traditional cold

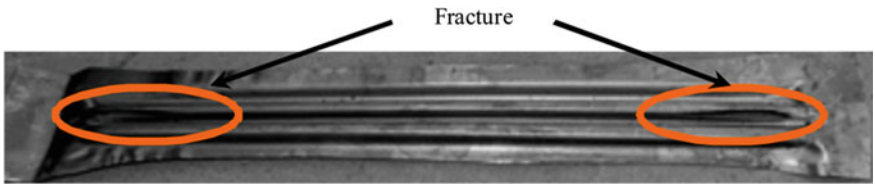


Fig. 2.12 Reinforced beam with direct method of hot stamping

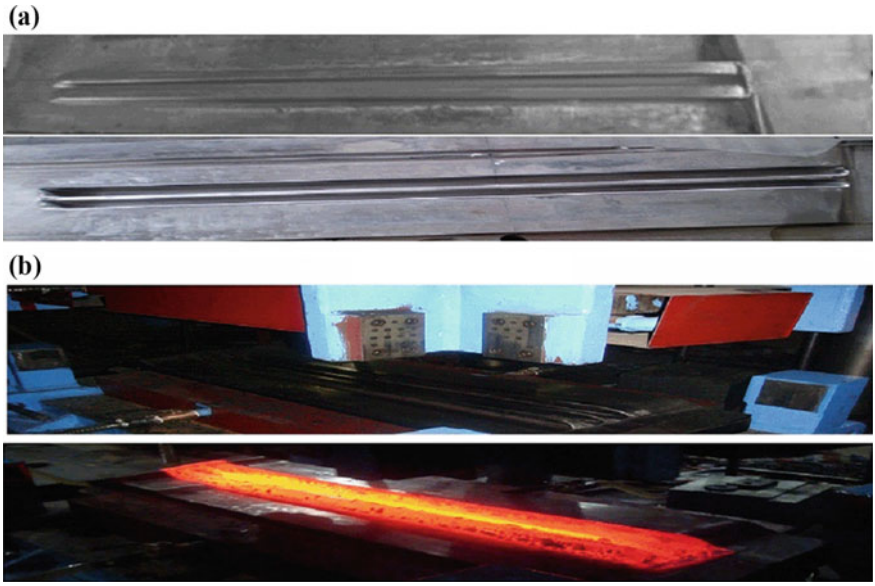


Fig. 2.13 Reinforced beam with direct method of hot stamping. **a** Preforming mold. **b** Final forming and quenching

forming. Afterwards, the preformed part is put into the furnance and fully austenitized at the temperature of 950 °C for 5 min before it is quickly sent into the dies with cooling system, as shown in Fig. 2.13b, for forming and quenching. The obtained hot stamping part is shown in Fig. 2.14. In order to verify the feasibility of forming process, microstructure and mechanical properties of some parts are tested. The results of tensile test for the samples cut from the enhanced beam are shown in Fig. 2.15. The stress–strain curve shows that the yield and tensile strength of the hot stamping part is more than 1000 and 1600 MPa, respectively. The above experimental results show that the enhanced door beam formed by indirect hot stamping meets the technical requirements of hot stamping [40, 41], which also proves the validity of the indirect hot stamping process and the design of hot stamping tools.



Fig. 2.14 Reinforced beam with multi-step method of hot stamping

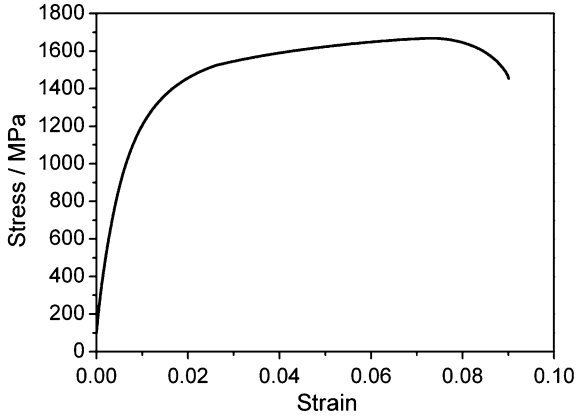


Fig. 2.15 Engineering stress–strain curve of the reinforced beam

2.1.3 Finite Element Simulation Analysis of Hot Stamping Technology

In the late 1980s, with the rapid development of computer technology and the maturity of finite element method, numerical simulation technology of sheet metal forming ushered in a vigorous development, which was driven by strong application demand in the world of automotive industry; and this technology is still in the ascendant.

There are three important signs of progress during this period

(1) The establishment of three-dimensional nonlinear shell theory made it possible to analyze the forming process of some complex parts, such as car body covers, the algorithm for contact and friction problems, took geometric nonlinearity into consideration;
(2) To promote the research of sheet metal forming simulation and investigate the reliability of numerical analysis algorithms, international research organizations have designed a series of standard questions, such as OSU (Ohio State University) standard questions, VDI (Verein Deutscher Ingenieure) standard questions, NUMISHEET numerical simulation of sheet metal forming standard questions. These questions aim to assess finite element softwares' performance of forecasting splitting, wrinkling, buckling and springback from different angles. The examination questions are related with simple parts and complex panels;

(3) A number of element finite element software has been developed and has taken certain standard questions previously mentioned. Some software, such as DYNAFORM, AUTOFORM, and PAMSTAMP, has already been widely applied in automotive industry. These software can solve high geometric nonlinearity, material nonlinearity, contact and friction problems occurred in forming process, so as to make predictions for wrinkling and fracture.

Great progress has been made in sheet metal forming simulation in recent years. Many international companies, especially automobile manufacturers, have established relevant sheet metal forming simulation systems to provide strong support for the stamping mold design, process design and mold test in terms of failure analysis and quality improvement. The well-known automotive companies of United States and Germany have taken stamping formability analysis as a necessary step in the development process, while automobile companies of Japan conducted formability analysis selectively.

However, in hot stamping, due to the effect of temperature, the material's flow stress and forming characteristics in the forming process will change constantly, making the finite element simulation analysis of the forming process much more complicated. Actually, hot stamping process of HSS sheet is a complex process with the interaction of the temperature field, stress field, and phase transformation field. First of all, most thermal and mechanical properties of sheet metal sheet such as the thermal conductivity, specific heat, elastic modulus, the flow rule, etc., depend on its temperature. Second, the thermal stress will produce due to the uneven temperature distribution at internal and external surface of sheet metal during cooling process. And large deformation in forming process can produce plastic work, most of which converted into heat energy and affect the temperature field distribution in turn. Under the effect of stress, the parameters such as initial temperature, finish temperature, and the rate of phase transformation are changed producing the so-called phase transformation plasticity at the same time. The microstructure changes in the process of phase transformation and influences the thermal and mechanical properties and formability. Volume expansion happens when the austenite changes into martensite or bainite, but uneven temperature distribution would lead to the difference in amount of phase transformation and different expansion rate, which can also produce phase transformation stress. During the quenching process, latent heat is released when the microstructure changes from austenite to martensite or bainite, which will influence the temperature field distribution. The start temperature of phase transformation and the final phase transformation amount is decided by both sheet metal temperature and cooling rate, while strain rate may also affect the thermodynamic properties and phase transformation field. Thus, the key to the finite element simulation analysis of hot stamping is the above field coupling analysis.

At present, although the generic software for sheet forming, such as Autoform, Dynaform and Pamstamp, have attempted to add hot stamping module, its commercial background makes them pay more attention to the calculation efficiency and the simplification degree in multi-field coupling hot stamping simulation model

is relatively bigger, which cannot meet the demand of comprehensive simulation study for multi-field coupling of hot stamping.

Research team of Professor Ping Hu from Dalian university of technology has taken more than 10 years to develop the KMAS (King-Mesh Analysis System) software system, which is a piece of high and new technology software with fully independent intellectual property rights. The KMAS was commercially available at the end of 2003 and successively provided technical support for China FAW, GM and other famous automobile and software enterprises, and became one of the global best partners of the UGS in United States. With the development of hot stamping technology, the application range of KMAS software system becomes much wider while the function to solve problem becomes stronger, too.

Based on the established constitutive equation coupling thermal, mechanical and phase transformation of HSS hot stamping, editors of this book, together with the other members in hot stamping team, have considered the interface heat transfer between blank sheet and dies. By using the heat transfer theory, the general shell temperature field finite element analysis theory and three-dimensional tetrahedral finite element theory, they developed the algorithm program, perfecting the pre-processing module and the post-processing module of HF/KMAS. By analyzing the change law of temperature field for shell and 3D tetrahedron units, the numerical simulation can obtain reliable temperature field, which can be used for further analyzing the coupling relationship of thermal, stress and phase transformation in hot stamping process to implement the simulation analysis of key variables as thermal, mechanical and phase transition of hot stamping in KMAS.

2.1.4 The Research Status of Hot Stamping

The material required by hot stamping is a special boron steel with high strength, which can be divided into coating hot stamping sheet steel and non-coating hot stamping sheet steel. The world's largest steelmaker Arcelor Group has developed the hot stamping sheet Usibor 1500 [1, 2, 5, 43] and then made it into mass production. Besides, this company also possesses the production patent of Al–Si coated hot stamping steel, whose characteristic is that the material organization is a uniform mixture of ferrite and pearlite after rolling forming, with a yield strength of 280–400 MPa and tensile strength over 450 MPa. After hot stamping, the organization transforms into uniform martensite with a yield strength of 1200 MPa and tensile strength 1600 MPa (3–4 times larger than ordinary steel's strength). Sweden's SSAB has developed and then produced hot-rolled quenched boron steel of Domex series, including 20MnB5, 27MnCrB5, 30MnB5, 33MnCrB5, 38MnB5, etc. The thickness, width and length of these plates are 1.80–12.0 mm, plate width 800–1600 mm and plate length 1500–13000 mm, respectively. After hot-rolling, its yield strength reaches 400 MPa, and its tensile strength reaches 600 MPa. After heating, the tensile strength of water quenching reaches 1480–2050 MPa, while the tensile strength of oil quenching reaches 1360–1845 MPa. In addition, Japan's

Nippon Steel and Kobe Steel, South Korea's Pohang Iron and Steel and other companies are able to produce hot stamping micro-alloy steel in batch production [38]. At present, all these major steel mills are making great efforts to develop high strength hot stamping steel with better performance.

China's Baosteel Group has developed and produced two types of hot stamping boron steel, which are cold rolled B1500HS and hot-rolled BR1500HS, and realized mass supply. It is China's largest supplier of hot stamping steel at present [52]. In addition, Anshan Iron and Steel, Tonghua Steel, and other steel companies have also been developing smelting and rolling process of hot stamping steel that can supply mass production.

Hot stamping technology of HSS was first used in the automotive industry in Europe. The application prospects and the complexity of research in hot stamping technology attracted the attention of scholars in the related fields. Thus, the hot stamping seminar is held during the international famous conference on Metal Forming after 2008, such as IDDRG2009, NUMIFORM2010, and METALFORMING2010 [41, 46]. Currently, three major research echelons [25] in the hot stamping technology of HSS have been formed according to the research time sequence. The first echelon is the European team represented by Germany and Sweden. The second is China, Japan and South Korea while the third is the United States and other countries.

Classified by research groups and research institutes, the main representatives are Lulea University of Technology in Sweden, University of Nuremberg in Germany, Technical University of MUNCHEN in Germany, University of Padua in Italy, Yokohama National University and Toyohashi University of technology in Japan. In addition, the Iran Arak University has also systematically studied the hot stamping principle and process for HSS plate [4, 20, 36, 37, 42, 44].

In China, there are a number of universities and research institutes, such as Dalian University of Technology, Jilin University, Tongji University, Shandong University, Shanghai Jiaotong University, Harbin Institute of Technology, Iron and Steel Research Institute, Baosteel Research Institute and Chongqing Automobile Research Institute, which have paid much attention to the study and development of hot stamping technology. According to their own actual situation and the relevant project from national ministries or enterprises, the above units are actively involved in correlational study of constitutive relation of hot stamping material, rolling experiment, stamping process, the simulation analysis, analysis of manufacturability, etc. [3, 7, 23, 24, 56, 57].

As the developer of domestic first hot stamping batch production line [13, 28, 45] with fully independent intellectual property rights, the research team of professor Hu Ping in Dalian University of Technology has conducted systematic basic experiment and simulation research on hot stamping technology about the thermodynamics constitutive relation of material, heat transfer analysis, process improvement, tool optimization design and manufacturing process [3, 8, 9, 17, 22, 53], and successfully established the constitutive relation coupling the thermal, stress and phase transformation [11, 27, 30–34, 49] for HSS hot stamping. In addition, they have also successfully developed the hot stamping simulation CAE module (KMAS/HF) (King-Mesh Analysis System/Hot Forming) [12, 14], which can accurately simulate

the formability of steel plate at elevated temperature, simulate and analyze the features of temperature field, stress field and phase transformation field in hot stamping process and be used for optimization design and manufacture of water cooling tools. They further investigated the basis about manufacturing of hot stamping hardness gradient composite material and parts and realized the tool design and the analysis of manufacturing process for hardness gradient hot stamping [18, 47, 49]. They put forward the method and main technical points suitable for the design of hot stamping water cooling tools [15, 54], and have successfully manufactured several tool sets, which have been applied to the products such as door beam, bumper, and the inner plate of B-pillar [16, 48]. Years of technological research and study have forged their leading position in the integration of industry-university-research-application for the hot stamping technology in China.

2.2 Hot Stamping Production Lines and the Key Equipments

Similar with the cold stamping parts, the acquisition of continuous and large quantity of hot stamping parts also need automatic production lines. However, the mechanical properties of boron steel sheet and the total hot stamping process are closely related to the temperature, resulting in the different requirements for the equipment on production line.

As shown in Fig. 2.16, hot stamping production line is comprised of such devices as anti-oxidation continuous ring heating furnace, fast transmitting device, high-speed hydraulic press, water cooling hot stamping die, laser cutting and shot blasting, etc. With the design and optimization for production line system based on virtual reality technique, the above-mentioned key equipment can be integrated into automatic production line with central control.

Due to technical difficulties and technology monopoly and blockade from foreign enterprise, China did not have the ability to develop the hot stamping Continuous

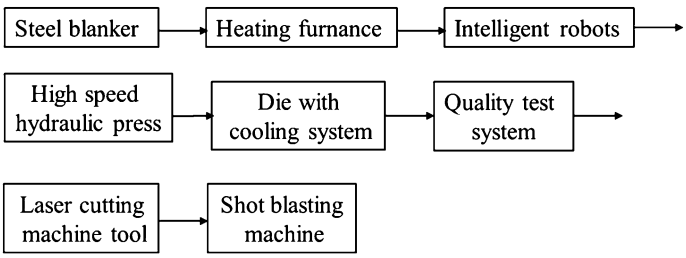


Fig. 2.16 Sketch of production line for hot stamping

ring heating furnace for long-term until JiLin VAFT auto parts co., LTD cooperated with Dalian University of Technology. After several years of continuous technological research, they developed the energy-saving heating system with completely independent intellectual property rights in china. Different from the tunnel furnace adopted by foreign production line, this furnace covers an area of only a quarter of the tunnel furnace and can save almost 30 % of energy from consideration of reducing cooling energy consumption and power-on and power-off consumption. Controlled by the servo device, it is able to ensure the furnace operating stably for a long term, and sheet metal can be heated to realize austenization in furnace stably. China's first hot stamping production line in VAFT with completely independent property right is shown in Fig. 2.17. It is mainly composed of high-speed hydraulic press, industrial Continuous ring heating furnace, water cooling tools, transport agencies, high-speed manipulator and automation control system, etc. This section will make a brief introduction of the key equipment and technology in hot stamping based on the independent developed hot stamping production line [6, 10, 19, 29].

2.2.1 *Continuous Ring Heating Furnace*

The continuous ring heating furnace used in the hot stamping should ensure that the blank is heated up to the setting temperature for a complete austenitization. At the same time, the high-temperature oxidation and decarburization should be avoided for those blanks without anti-oxidation coating. The continuous ring heating furnace has its unique core technology in comparison with other heating furnaces, and its brief descriptions are as follows:

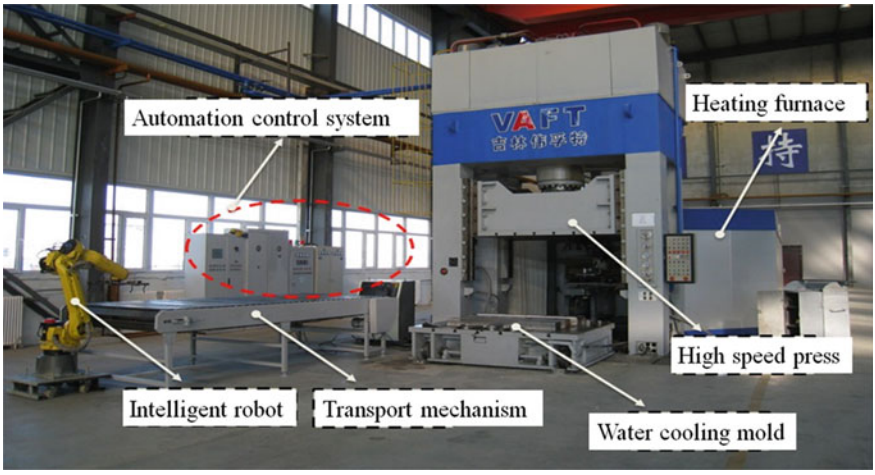


Fig. 2.17 The first domestic hot stamping automatic production line

(1) Most of the automotive HSS blank is sheet. The sheet should be heated up to the specified temperature and then hold heat in order to be fully austenitized. Therefore, the temperature distribution in the heating furnace is required to be homogenous;
(2) For the steel sheet without protective coating from oxidation, its oxidation and decarburization is very serious at elevated temperatures. Therefore, the furnace is needed to take strict measures of gas protection;
(3) All the parts of the heating furnace run under the conditions of long term and continuous operation at a high temperature (over 800 °C), so their expansion property, high temperature fatigue, failure rate and maintainability must be taken into consideration;
(4) Hot stamping production line needs to satisfy the setting cycle time, so it needs the equipment for loading or unloading which can meet the requirements for the high-temperature work and corresponding automatic control system;
(5) One of the purposes of hot stamping technique is to save energy and protect environment, thus it also requires energy-efficient heating furnace.

Figure 2.18 shows a self-developed energy-efficient continuous ring heating furnace, namely ring rotary hearth heating furnace [14]. The core techniques of ring rotary hearth heating furnace are the deformation of the moving spindle with resistance to high temperature, moving bias control, thermal fatigue durability, etc. By using infrared temperature measurement technology and thermocouple temperature measurement technology, the temperature distribution inside the furnace under the no-load and full load condition is monitored, which is used for further optimal design to achieve the temperature control and monitoring system inside the

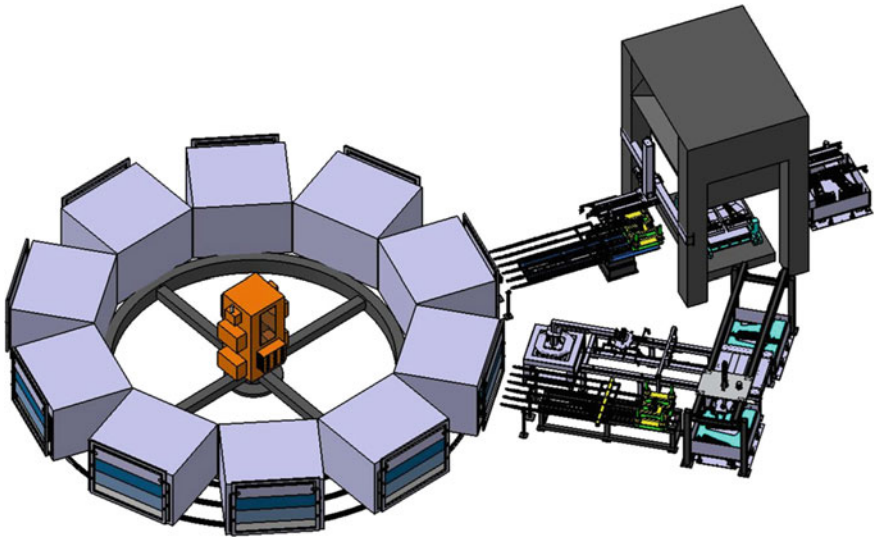


Fig. 2.18 Continuous ring heating furnace for hot stamping

heating furnace. In order to ensure the reliability of furnace, appropriate materials are required to use to produce the core spindle and blade of the converter. Furthermore, the high-temperature resistant property and thermal fatigue property of main heat resistant furnace parts should be tested and validated. Besides, the reliability and precision of the core spindle's continuous operating should also be tested and validated. In order to prevent sheet from oxidation and decarburization at elevated temperature, this continuous ring heating furnace is equipped with anti-oxidation gas-filled device of controlled flow and pressure.

2.2.2 *High-Temperature Resistant Robot Arm and Automatic Transfer Device for Loading and Unloading*

During the forming process, the blank is heated to be austenitized in a heating furnace at a temperature ranging from 800 to 1000 °C. And then high-temperature manipulator is used to remove the blank from the furnace and put it into die for forming and quenching, as is shown in Fig. 2.19. In this process, the wireless temperature testing sensor is placed on the robot arm in order to make online detection of the temperature changes of sheet transfer. Then the rotating speed of the robot arm is controlled according to the temperature information collected by the sensors. The information about temperature is transferred to the total console through the data lines, which can ensure the sheet temperature would not decline out of the prescribed limits in the transfer process of high-temperature sheet. The main structure of the jaw is clamp-like attached with reticulation to avoid excessive force and the drop of the sheet. The high-temperature position sensors are placed on the arm of robot to find accurate position in order to guarantee the product quality.

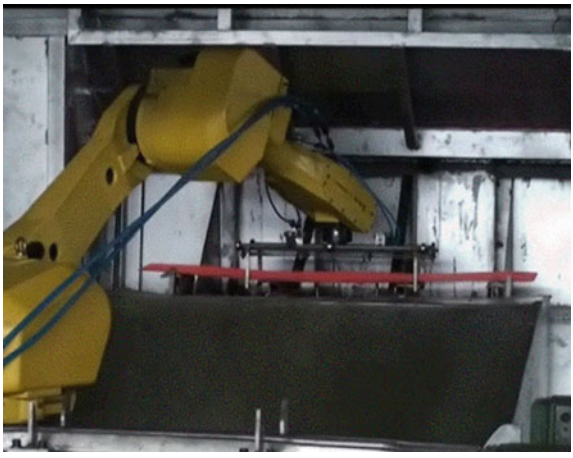


Fig. 2.19 Intelligent robot arm with high temperature resistance

The design and manufacture, sensing technology, automatic control technology and reliability of high-speed intelligent transfer device (including the high-temperature resistant tooling) are the key techniques which are needed to ensure that high-temperature steel sheet can be put into shaping dies rapidly and accurately, and that the stamping parts can be removed from the dies after quenching, in the hot stamping production line. As shown in Fig. 2.20, after automatic feeding and austenitic transformation in the heating furnace, the sheet is transferred to the specified position rapidly and accurately by the automatic unloading device to ensure the accurate subsequent operations of the robot arm.

High-temperature resistant gripper is designed and manufactured for automotive structural parts of different sizes and shapes. Cooperating with the high-speed intelligent transfer device, the gripper completes the grab and delivery of hot sheet under the precondition of process requirements. In order to achieve the reliable mass production, the control system of high-speed intelligent transfer device and the temperature monitoring device attached on transfer device are set up in the central control system. This temperature monitoring device and die temperature monitoring device are combined together to form a temperature collection system in the production line. Thus, the temperature parameters in production are recorded, which is helpful to optimize the process, predict the property of the steel sheet and die fatigue, etc., according to the actual production data.

2.2.3 *Key Technologies for Design and Manufacture of Hot Stamping Dies*

After the steel plate is heated in the furnace, its forming into expected shape and strengthening simultaneously must rely on the dies with cooling system. The key technologies for design and manufacture of hot stamping dies are



Fig. 2.20 Feeding by automatic loading/unloading device after transfer process

(1) After the steel plate is heated, its ductility will increase, while its strength will decrease. In order to avoid cracking and wrinkling of sheet, the die clearance and its accuracy of manufacture should be arranged reasonably;
(2) In order to meet the martensitic transformation and the uniformity of microstructure distribution, the cooling ducts' design should be optimized to ensure that the sheet can be cooled uniformly and formed at a specified cooling rate;
(3) Hot stamping dies work in an environment where the temperatures are continuously changing between the high temperature and low. In this process the dies withstand expansion and contraction. Thus, the materials for dies and processing technologies need to be taken into consideration for a proper service life.

According to different performance requirements of the products, the layout of the dies with different pipes is shown in Fig. 2.21. Figure 2.21a shows a layout of uniform cooling pipes, in which the hot stamping parts can be obtained with uniform martensitic microstructure [40]. Figure 2.21b shows a layout with nonuniform cooling pipes, in which the microstructure of the parts obtained is segmented, continuous and mixed [26]. Figure 2.21c shows a layout of temperature variable district cooling tools with both cooling pipes and heating pipes, in which the hot

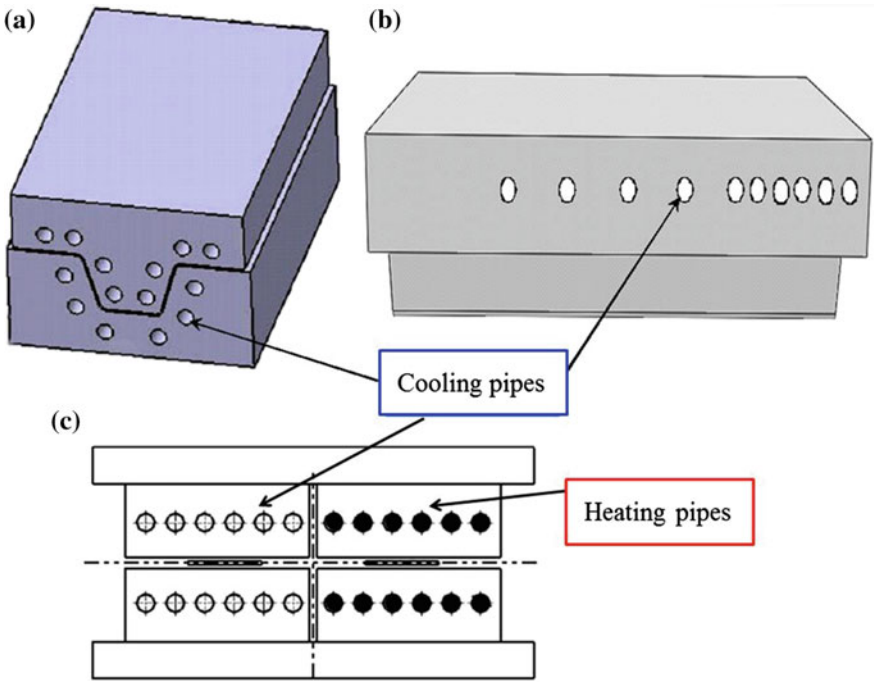


Fig. 2.21 Sketch map of die cooling pipes. **a** Layout of uniform cooling pipes. **b** Layout of non-uniform cooling pipes. **c** Layout of tools with both cooling pipes and heating pipes

stamping parts with feature of changing hybrid organization and continuous gradient hardness can be obtained.

Figure 2.22 shows a picture of die for experiments. This water cooling die made from special material possesses a cooling system, in which the pressure and the flow can be servo-controlled [41]. As the hot stamping die, especially its surface, experiences frequent hot and cold alternation during the stamping process, it is easy to result in fatigue failure in the process of mass production. Therefore, hot stamping die materials with high-temperature resistance, high wear resistance and high fatigue resistance should be developed on the basis of existing heat resistant die materials.

2.2.4 High-Speed Hydraulic Press for Hot Stamping

Hot stamping press should possess the functions of quick die closing, stamping and pressure holding. At present, the presses for cold stamping cannot be applied to hot stamping because the conventional hydraulic press has a low speed of die closing and the mechanical press does not have the function of pressure holding. Thus, it is necessary to tailor a press for hot stamping [1].

The hydraulic press for hot stamping is shown in Fig. 2.23. On the basis of the accuracy requirement of forming parts, the finite element models of the hydraulic press with the coupled dies and stamping parts are built and analyzed. From the analysis in detail, the stiffness, strength and modal of the press are obtained. Finally the structures are optimized for the hot stamping purpose.

The design of the cylinder seals of high-speed hydraulic press for hot stamping is the core part of the design of the hydraulic press sealing. Lots of hydraulic seal experiments should be carried out during the design process. Meanwhile it is necessary to combine the seal combinations of Lancaster closure-Y ring seal-guide ring provided by foreign seals manufactures, with the purpose of searching for the seal combinations of hot stamping press which is suitable for independent

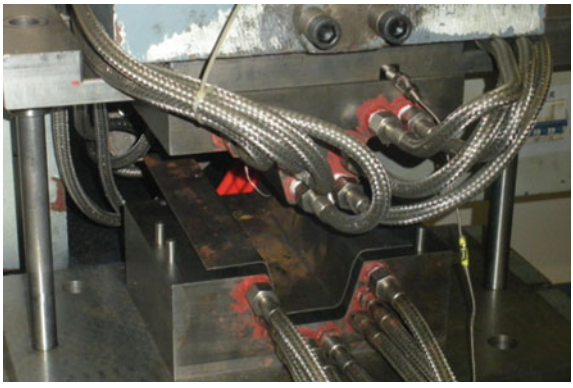


Fig. 2.22 Water cooling hot stamping die for experiments



Fig. 2.23 800t hydraulic press for hot stamping

development. Only by this way, can we ensure the sealing effectiveness and stable pressure of hydraulic press under high-speed operation in order to meet the accuracy requirements of forming stampings.

2.2.5 Central Intelligence Control Automatic Integrated System

Due to the high-temperature heating in hot stamping production line, sheet metal in red state is extremely easy to deformation and many factors like high-temperature condition determine that the loading device should use special catcher, which should connect to the mechanical arm to realize the up and down movement of sheet material. The design of catcher should only consider the high-temperature state of blank, but also ensure the smooth and steady during transfer process and decrease the local cooling in the contact area of red blank as far as possible. To minimize the oxide on the surface of the steel plate, feeding time should be as short as possible. By using the mechanical arm equipped with complex motion structure computer, together with AC variable frequency control system and hydraulic buffer with composite positioning with electric braking, it is able to realize high speed, precise, stable positioning and synchronous control of take time. In addition, the loading device should also be equipped with temperature monitoring device, such as infrared temperature measurement, inspection, etc. Based on the data obtained from actual production process, the function of process optimization, performance test, fatigue performance prediction and process fault self-locking can be realized, together with the closed loop control system.

Based on TOP–DOWN system design and idea of industrial integration, to build global flexible, efficient, stable, reliable and integrated controllable hot stamping production line is the key aspect to realize equipment nationalization. Integrated system should first complete the top-level design, then decompose layer by layer to guarantee each functional unit meets the unified requirement of system accuracy and reliability, realizing the central controlled industrial network online integration system.

The control system should adopt highly reliable and stable field bus industrial network technology to form three-step control system as enterprise, technology and equipment level, while the external-related equipment are controlled and interlocked by the bus control protocol. In solving the common key technical problems in the major functional units, equipment such as heating furnace, high-speed press and high-speed conveyer are preset according to the take time of production to realize synchronous linkage and system integration, and ensure the reliability and stability of the local hot stamping production line. The central control system is shown in Fig. 2.24.

2.2.6 *Subsequent Shot Blasting, Trimming, and Punching Equipment*

HSS for hot stamping can be divided into two kinds: one with protective coating and the other without protective coating. Boron steel with protective coating can avoid high-temperature oxidation effectively during the hot stamping process. While oxide scale formation occurs in the process to the boron steel without protective layer. In order to ensure the surface quality of components, shot blasting is needed to remove the scale generated by high temperature from hot stamping components. Figure 2.25 shows the shot blasting equipment and the work site. Of course, shot blasting should not reduce the dimensional accuracy of components.

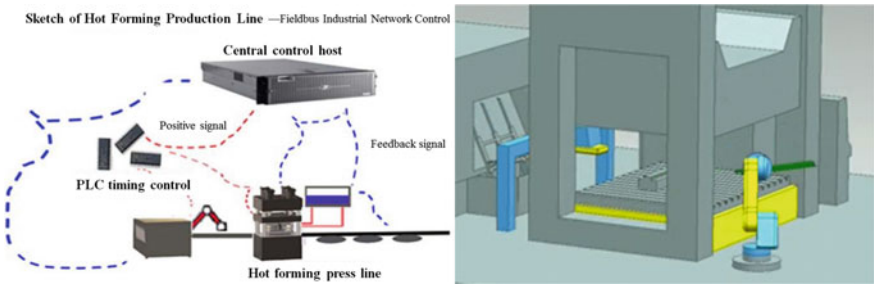


Fig. 2.24 The schematic diagram of domestic hot stamping production line with central control network



Fig. 2.25 Shot blasting equipment

Hot stamping or reinforced beam which is made by steel without protective coating of anti-oxidation and anti-decarburization after hot stamping is shown in Fig. 2.26. It can be seen from the figure that there is scale on the sample surface. Hot stamping door reinforced beam product after laser cutting and shot blasting which meets the requirements of size and surface treatment is shown in Fig. 2.27.

In terms of cold stamping, dies are used for batch processing of trimming and piercing. But for hot stamping of steel plates, it is hard to use the dies to trim or pierce due to the high strength of parts. The approach of laser cutting is often used to achieve it. The so-called laser cutting is to use the released energy generated by the laser beam falling on the workpiece surface to make the workpiece melt and evaporate, so as to achieve the purpose of cutting and engraving. The laser cutting has the advantages of high precision, fast cutting, few cutting pattern restrictions, automatic layout and material-saving, even cuts, low processing costs, etc. It may gradually improve or replace conventional cutting equipment. It should be noted



Fig. 2.26 Door reinforced beam by hot stamping (without protective coating)

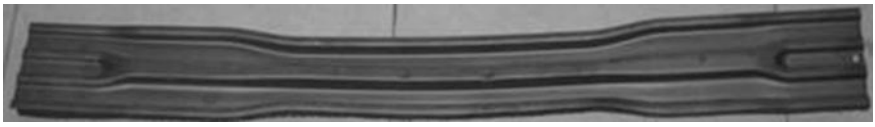


Fig. 2.27 Door reinforced beam after shot blasting

that with the method of laser cutting, process parameters should be better controlled to avoid parts annealing under local high temperature which will influence the properties of the final parts.

2.3 Summary

This chapter mainly gives a brief instruction of the application of HSS hot stamping technology, the technological process, research status, the automatic production line with main equipment and the key technologies to systematically describe the basic content of hot stamping advanced manufacturing technology, so that readers are familiar with the research content in the following chapters. In addition, the finite element simulation analysis of hot stamping is particularly introduced. Characteristics of thermal-stress-phase coupling in hot stamping process and the role of multi-field coupling thermal forming simulation and thermal mechanical material parameters in hot stamping research are emphasized. This chapter also focuses on the hot stamping production line and the main equipment and elaborates the special requirements of hot stamping equipment comparing to traditional equipment in order to provide important guidance for the readers engaged in equipment development.

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