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Novel Research Pertaining to the Forming Defect Properties of High-Strength Steel Plate during Hot Stamping Procedures

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Abstract:- Nowadays, the stamping process has become one of the commonly used techniques in metal processing, which is achieved through processing methods with high productivity and low material consumption. For the production of large quantities of parts and components, compared with other metal processing and forming technologies, it can effectively save more money, time and labor, and facilitate the implementation of mechanized and automated production modes. For instance, in the field of automobile industry, the proposal of lightweight can effectively solve the problems of environmental pollution and energy crisis. Therefore, high-strength steel plate, as a typical lightweight material, has been widely used in the automobile manufacturing industry. However, with the improvement of the tensile strength of high-strength steel, its plastic properties are greatly reduced. During the cold stamping process, the sheet will have cracks, wrinkles, corrosion, orange peel and other forming defects, which will reduce the forming accuracy of the sheet. Over time, it will limit the use of high-strength steel in the car body. On the other hand, hot forming technology is widely used in automotive engineering due to its advantages of good forming performance, small forming load, small springback, and high strength of parts after quenching. Therefore, it is one of the most significant methods that stamping high-strength steel as components in various engineering fields. However, it is inevitable that the stamped parts will have forming quality defects in the process of hot stamping. For this reason, this paper studies the defect analysis and presents quality control measures of high-strength steel stamping.

***Keywords**: High-Strength Steel, Lightweight, Hot Stamping, Forming Defects.*

I.APPLICATION OF HIGH-STRENGTH STEEL

In the modern automobile manufacturing industry, lightweight has become one of the hot spots in this research field, and it is also one of the most advanced locomotive technologies. The concept of lightweight is based on the premise of ensuring strength and safety performance, reducing the overall weight of the car to improve the power utilization rate of the car. At present, the commonly used materials to realize the lightweight of automobiles mainly include: carbon fiber, aluminum alloy, magnesium alloy, titanium alloy, engineering plastics, composite materials and high-strength steel. High-strength steel plate is obtained by strengthening method on the basis of low-carbon steel plate as the tensile strength is greatly enhanced. Because of the high strength characteristics, the mechanical performance requirements of the car body can be maintained even when the thickness is reduced, thereby reducing the weight of the car. As a result, after the concept of lightweight is proposed, it has promoted the innovation and development of the automotive industry and promoted the development and application of a large number of technologies, thereby greatly improving the application of high-strength and ultra-high-strength steel in various fields. [1]

II.HOT STAMPING TECHNOLOGY

According to the difference in tensile strength, high-strength steel in the automotive field is mainly divided into ordinary high-strength steel and advanced high-strength steel. When the tensile strength is between 270MPa and 700MPa, it is defined as ordinary high-strength steel (HSS). As for advanced high-strength steel, it is seen as the tensile strength is above 700MPa. In addition, when the tensile strength of advanced high-strength steel is higher than 1000MPa, it is called ultra-high-strength steel (UHSS) [2]. And the literature [3] gives the distribution of tensile strength and elongation of different steel grades, as shown in the figure 1.

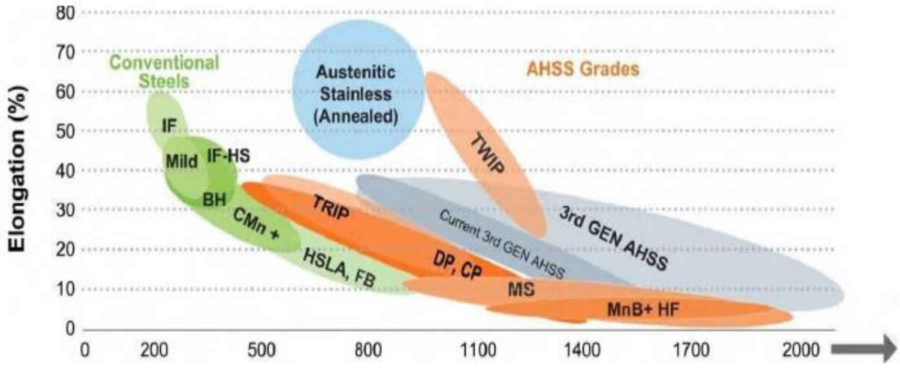


Figure 1 Tensile Strength (MPa) [3]

The strength of the low-alloy high-strength steel plate after cold stamping can reach 800-1000MPa, which reflects other shortcomings such as large forming load, difficult to control springback after stamping, and poor dimensional stability of parts, so traditional cold stamping methods are difficult to solve high strength Steel plate on the problems encountered in automobile manufacturing. Therefore, in order to satisfy both low forming force and ultra-high strength forming technology, many scholars have proposed hot forming technology suitable for low alloy high strength steel. [4]

Hot stamping forming technology is to heat the sheet to austenitizing temperature and then form and quench to obtain a high-strength martensitic structure, so that the low-yield-strength steel sheet is converted into ultra-high-strength parts, the strength of which is between 1500-1700MPa. The principle diagram of hot stamping forming technology is shown in the figure below. [5]

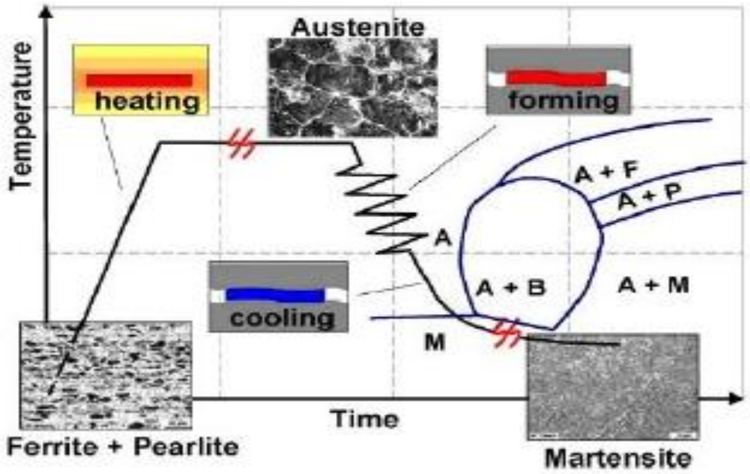
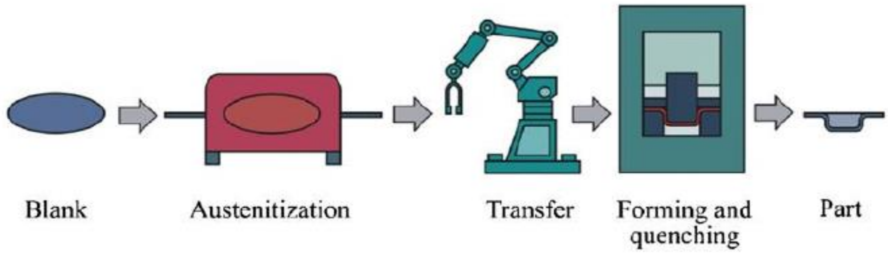


Figure 2 The forming principle of high-strength steel subjected to hot stamping [5]

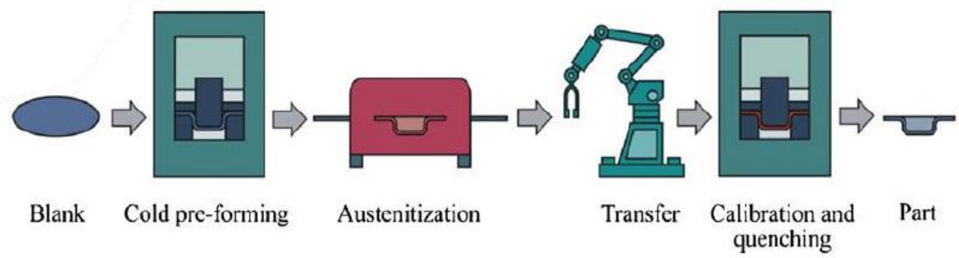
Hot stamping can not only make the material plasticity and forming performance good, but also significantly reduce the forming load, which means that there is no need for cumbersome forming steps, and the high-strength steel plate can be stamped into a complex stamping machine only once. More importantly, it solves the problem of springback defects of the plate after stamping, thereby greatly improving the forming accuracy of the parts. [6-8]

In more depth, the hot forming process is mainly divided into direct hot forming [4] and indirect hot forming [9], the principle is shown in the following figure (a) (b). Direct hot forming is a process in which the sheet material is heated to complete austenitization, and then forming and quenching are completed on the mold at the same time. Indirect hot forming is the process of pre-forming the sheet metal on the mold to complete more than 90% of the deformation [10], then austenitize, and then achieve complete deformation and quenching on another mold. The difference between the two is that the entire process of indirect thermoforming is completed on two sets of molds.

The scope of application of indirect hot forming is generally aimed at the forming of deep-drawn parts, and compared to direct hot forming, indirect hot forming has more forming procedures and more complicated processes. Therefore, for the production of most commonly used high-strength steel hot-formed parts, direct hot forming is more widely used.



(a) Direct hot stamping



(b) Indirect hot stamping

Figure 3 Process flow of two hot forming methods [4]

III.NUMERICAL SIMULATION RESEARCH

Numerical simulation technology and widely used in high-strength steel hot forming research, and accurate simulation is inseparable from the reliable material constitutive equation. At present, the constitutive relationship of materials is also the current way to describe the constitutive equation through equivalent stress and strain. One is to obtain the stress-strain relationship by performing a uniaxial tensile test on the material, and then use the hardening curve equation. Ludwik [11] first explained the stress-strain relationship of the material under plastic conditions and established the following formula :

$$\sigma = \sigma_0 + k\varepsilon^n \tag{1}$$

Where σ_0 is the initial yield stress of the material;

k and n are the material constants.

After that, Swift [12] further and more completely proposed the fitting formula of the material in the plastic deformation stage based on a large amount of experimental data:

$$\bar{\sigma} = k(\varepsilon_o + \bar{\varepsilon})^n \tag{2}$$

$$n = \frac{[\ln(\bar{\sigma} + c) - \ln k]}{\ln(\varepsilon_0 + \bar{\varepsilon})} \tag{3}$$

For the study of material flow properties during hot forming, a large number of scholars have proposed relative physical and empirical models. Eriksson et al. [13] studied the high-temperature mechanical behavior of the high-strength boron steel Docol Boron 02 produced by Saab Automobile Company through high-temperature compression tests and expansion tests, and gave the stress-strain curve and thermal expansion data of the material at different temperatures and strain rates. Johnson [14] and other scholars established a high-temperature material flow model exponentially related to temperature, which is expressed as follows:

$$\sigma(\varepsilon,\dot{\varepsilon},T)=(A+B\varepsilon^{n})(1+C\ln\frac{\dot{\varepsilon}}{\varepsilon_0})[1-(\frac{T-T_0}{T_f-T_0})^{m}]$$

(4)

Hochhildinger [15,16] conducted a series of thermal-mechanical tests on a high-speed expansion instrument in order to obtain the flow properties of the material. As a result, it was proposed that the Tong-Wahlen model has a better fitting effect. Other commonly used models include Nemat-Nassert model, Voce-Kocks model, Jackson-Cook model, Norton-Hoff model, etc. [17]

As an important aspect of the numerical simulation technology of hot stamping, the introduction of a wide range of plate and shell element models into the formulation of the thermoplastic large deformation finite element is one of the first issues that many scholars pay attention to. The research on the simulation of sheet metal stamping began in the 1960s. Ghosh and Kikuchi [18] first performed numerical simulations of the hot stamping process. In Japan, Makinouchi and others from the Sheet Metal Forming Research Association first developed ITAS3D based on the static explicit solution algorithm, and then many Japanese car dealers applied this algorithm to product development. [19-23]

Hippchen conducted numerical simulation through MAT_244, and the results showed that there was a large error between the numerical simulation and the experimental results. Therefore, the Lee model was used to describe the non-diffusive phase change behavior to improve the accuracy of the numerical simulation, and the results were substituted into the MAT_248 material model. The results show that the accuracy of numerical simulation has been significantly improved. [24] In South Korea, Park [25] and others performed a numerical simulation on the hot forming process of the body B-pillar and analyzed its sheet flow characteristics. Mohr[26] et al. used 22MnB5 specimens to conduct biaxial plastic tests and biaxial rupture tests under high temperature conditions. During the test, the stress and strain parameters of the specimens were recorded. Finally, the test combined with the Abaqus finite element simulation software. The test results clarified that the biaxial plasticity and biaxial rupture models can better predict material cracking during the forming process. Olsson [27] substituted the Akerstrom phase transition model into the MAT_244 material model of the Ls-dyna finite element software, and realized the application of the thermoforming process in commercial development.

In the experimental research, Jeon [28] and others made a self-made test device, which completed the forming test under different stamping speed, cooling time and blank rolling direction at high temperature. Zimmermann [29] tempered the parts by flame heating, and the results showed that when the tempering temperature reached the highest, 793℃, the strength of the parts was the lowest at this time, which was 580MPa. Nikravesh [30] et al. used a thermoforming dilatometer to conduct a hot forming experiment, and studied the influence of the deformation process and cooling rate on the volume fraction of each microstructure after forming, and based on the experiment, the CCT curve and DCCT curve of 22MnB5 were drawn.

IV.HIGH-STRENGTH STEEL STAMPING DEFECTS

➢ *The Fracture of Hot Stamping*

Fracturing defects will occur when advanced high-strength steel is processed by stamping. During the process, the thickness requirement of advanced high-strength steel can be reduced by 4%~20% compared with the normal thickness. Once the thickness of advanced high-strength steel is lower than the normal thickness during the processing, it will not only weaken the rigidity of the generated parts, but also in more serious cases. It can also lead to cracking or even scrap of advanced high-strength steel. It can be seen that cracking is one of the serious quality problems in the stamping process of advanced high-strength steel. According to the degree of fracture, it can be divided into micro and macro cases. Micro-fracture refers to the cracks and cracks that can not be seen or can only be seen but can not be seen with the naked eye, so it is necessary to use some special test equipment to check the defect position. Although micro-fracture will not cause the processed parts to be scrapped directly, in fact, the part of micro-fracture has lost its original function and shortened the service life. Macro-cracking refers to visible cracks and breaks. This obvious stamping forming defect has caused parts made of advanced high-strength steel to be unusable. In other words, when there are macro-cracks in the plate, the product is scrap.

The rupture limit, as the name implies, is the ultimate strain at which a plate breaks.In addition, sheet metal will also wrinkle and neck down during stamping [31].During stamping, wrinkling is a form of failure of sheet metal under press-press or pull-press conditions. Therefore, wrinkling is usually prevented during stamping by increasing the blank holder force of the sheet.On the other hand, it also increases the tendency of material rupture [32, 42] while increasing the blank holder force.Therefore, in the 1960s, Keeler [33] and Goodwin [34] proposed the concept of Forming Limit Diagram (FLD). As shown in the figure below, after a great deal of experimental research by Keeler, Keeler defined the two-way principal strain of the material in a plane rectangular coordinate system.In order to plot the right half of the forming limit, the longitudinal and transverse coordinates of the coordinate system are plotted with the limit strain at the time of material fracture.Goodwin then draws the left half of the forming limit diagram through tensile tests, describes the limit strains of each state in a rectangular coordinate system, and completes the forming limit diagram by connecting the forming limit strain points one by one.

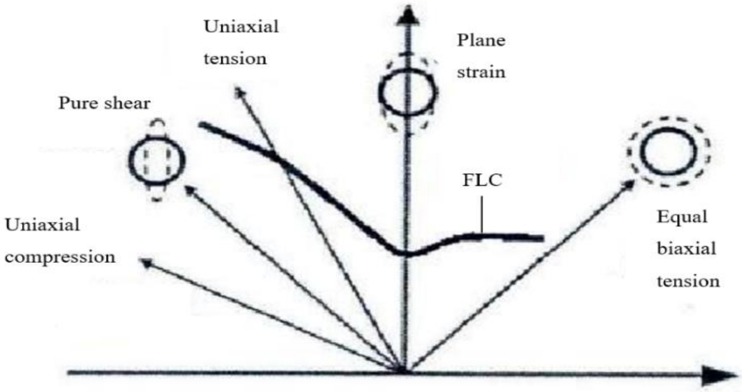


Figure 4 Forming Limit Diagram[34]

At present, some scholars have done a lot of experimental research on the acquisition of forming limit diagram, and according to the stress form of plates, the existing test methods are mainly divided into two types: flat surface method and curved surface method. Nakazim test method is also one of the most common methods used in surface method [35]. It is by placing the plate with printed grid between the blank holder and the die and pressing the sample with the blank holder, while the die expands the sample and stops pressing once it breaks or necks.

- *Hot Stamping Corrosion*

The high-strength plates used in traditional thermoformed steel are mainly ordinary high-strength steel plates without any processing, but after long-term use, many serious safety hazards have been exposed, the most serious of which is oxidation and decarbonization during heating. Choi et al. [36] showed that the surface decarburization of hot-formed steel is as high as 30 μm. As shown in the figure below, it is found that the structure of the central layer of steel plate after hot-stamping is martensite, while the surface is mainly ferrite and pearlite due to the low carbon content.

The use of automobiles is mainly exposed to long-term environment full of oxygen, dust and oxygen. Some countries, even the climate change is more intense, which makes parts of high-strength steel plate used in automobiles suffer from long-term harsh environment erosion. According to the survey data, the economic loss caused by automobile corrosion worldwide is as high as 150-210 US dollars annually. The corrosion modes of automobiles mainly include point corrosion, crevice corrosion and stress fatigue corrosion. Therefore, the existence of corrosion problems has led to the promotion and application of traditional high-strength steel. In order to overcome the corrosion problems faced by traditional bare sheet during thermoforming, an additional protective means is added to the surface of steel plate, which becomes a corrosion-proof method for stamping of high-strength steel plate. Among them, the most common is galvanized high-strength steel. The surface zinc plating layers are Al-Si coating and Zn coating. At present, the research on Al-Si coating is very early and mature. As for zinc coating, as a new coating method, it is because zinc in the coating can provide cathodic protection for the substrate.[37,38] Seok et al. [39] studied the change of the drawing depth, load and coating of cup-shaped parts under different heating temperatures and heating times. The test results show that the galvanized sheet is highly sensitive to process parameters during hot stamping, and the traditional bare sheet hot stamping process can not be fully suitable for hot stamping of galvanized sheet.

- *Orange Peel Defects*

High-strength steel plates often appear rough on the surface of the steel plate during the stamping process, which is also known as the "orange peel" phenomenon, which affects the appearance quality of parts and makes the number of waste products increase.High-strength steel plates often appear rough on the surface of the steel plate during the stamping process, which is also known as the "orange peel" phenomenon, which affects the appearance quality of parts and makes the number of waste products increase. From the perspective of the steel plate production process, the steel plate was not flattened during the continuous annealing process of cold rolling, which resulted in the failure to eliminate the yield platform and internal stress of the steel plate. In addition, the shape of the punched parts was complicated, which caused the steel plate to form "orange peel "phenomenon. Many scholars have done many researches on the defects of orange peel, for example, the three-dimensional microstructure of orange peel has been mapped by X-ray tomography. [40] Literature [41] pointed out that excessively coarse ferrite grains and "mixed crystal" structure are one of the important reasons that cause "orange peel" defects on the surface of stamping parts. Moreover, the relationship between the surface texture and roughness of the steel plate during the in-situ stretching process can be obtained through orientation mapping, atomic microscope, and profilometry. [42] The electron backscatter diffraction (EBSD) technique explains the relationship between the grain orientation and the surface shape of the orange peel. [43]

Therefore, the orange peel defect has an inseparable relationship with the grain size. In more depth, the literature [44-45] reveals that the surface roughness of the material is in direct proportion to the grain size through experimental studies. The coarser the grain, The rougher the surface of the material, the more likely it is to produce orange peel defects.

V.CONCLUSION

In order to meet the design requirements of the lightweight concept, the automotive body structure design and manufacturing industry continue to develop new materials and new technologies. Therefore, high-strength steel plates with comprehensive advantages in strength, rigidity, impact resistance, recycling, and low cost have attracted more and more attention in the lightweight design of car bodies.

Hot forming of high-strength steel, as an important technology for automobile lightweight, has played a huge role in promoting energy saving and emission reduction. However, many problems have been found in the production and use of traditional steel plates. Cracks, wrinkles and orange peel defects formed in the process of high-strength steel stamping. In addition, due to the lack of protection on the surface, oxidation and decarburization will occur during the heating process, and the parts are prone to corrosion during use. Therefore, the introduction of high-strength steel surface coating technology, in which galvanized sheet as a common surface immersion plating method is used in high-strength steel. Galvanized high-strength steel can effectively solve the problems of oxidation and decarburization during heating. At the same time, the zinc coating can provide cathodic protection for the substrate during use, thereby extending the service life of the parts.

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