Optimization of laser cutting technology for hot stamped high-strength steel part and product quality control

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In this paper, the laser processing technology and quality control of hot stamped parts made of high-strength steel are studied. Through in-depth on-site practice and analysis, combined with the exploration of laser cutting burrs on complex curved parts, a solution to the causes of cutting burrs is proposed. The research results show that factors such as cutting corner height and focal point position, cutting nozzle and cutting air flow, deviation between the digital model and the actual workpiece, cutting power and corner speed, and the influence of the positioning of the workpiece fixture play a key role in laser cutting. To address these problems, this study proposes effective solutions by adjusting the focal point position, optimizing the cutting nozzle type, and changing the cutting parameters. Eventually, after practical verification, these measures drastically reduce the corner burrs and solve the problem of burns on the cut parts while improving the efficiency of part debugging, so that the cutting quality is significantly improved.

Keywords: High strength steel; Hot stamping; 3D laser cutting; Complex surface; Defect analysis.

1. Introduction

With the development of automobile lightweighting and electrification, the hot stamping and forming technology of high-strength steel has gained wide application to meet the demand of lightweight and safety of automobile body [1,2]. In order to solve the quality and efficiency of cutting and punching the high strength and hardness of hot stamped parts, laser cutting has gained important applications. Laser processing can realize high-precision cutting, punching and contouring of various metal materials, which can meet the requirements of lightweight body manufacturing for precise manufacturing of parts. The key technology for integrated hot stamping of multiple parts is laser welding, and the application of laser welding processing is gaining large-scale application [3,4], which further promotes the application of the technology from laser dropping to laser welding. Lightweight body usually involves complex structural design and curved surface parts processing, and laser processing technology can flexibly cope with a variety of complex shapes of processing needs, to achieve precision processing of complex surfaces. In addition, laser cutting has a smaller cutting width and heat-affected zone, which can reduce material waste and help realize the lightweight design of body parts [5].

However, laser cutting is different from traditional mold blanking, which has its own characteristics for process and quality control. Through a comprehensive understanding and mastery of the process and characteristics of laser processing, it can effectively reduce the defects of laser processing, improve production efficiency and reduce costs.

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2. Characteristics of hot stamped formed parts and cutting elements

Hot stamping forming components are typically mandated to possess robust strength and hardness, meeting the stringent demands of lightweight and safety in automobile body design. These components often boast intricate geometries and structures, necessitating meticulous machining and forming processes. Throughout the hot stamping procedure, the metal material is subjected to heating to enhance its ductility and plasticity, all while demanding a high level of form precision and surface quality in the final product.

The comprehensive analysis of laser cutting elements in the processing of hot stamped and formed parts encompasses several crucial considerations. Firstly, the selection of laser power and focus must be tailored to the type and thickness of the material to achieve exceptional cutting and drilling quality. Secondly, the optimization of cutting speed and laser processing parameters is essential, requiring adjustments based on material characteristics to optimize cutting speed, gas assistance, spot shape, and other parameters, ultimately achieving efficient and precise processing. Additionally, ensuring the quality of the cutting edge and controlling the heat-affected zone are critical, necessitating the reduction of thermal impact and oxidation issues through process and parameter optimization to achieve high-quality cutting. Finally, for the processing requirements of multi-component integrated hot stamping parts, laser stitching technology enables efficient parts integration and connection. This technology demands high cutting accuracy for laser cutting dropouts and represents a superior technical choice for enhancing production efficiency and minimizing material waste.

3. Common cutting defects and problem analysis

3.1. *Laser beam focus position and cutting burrs*

The correlation between the focal position of the laser beam and the workpiece holds paramount significance in laser processing. The choice of focus position significantly impacts processing efficiency, quality, and outcomes.

The focal position is meticulously adjusted based on the material, thickness, and processing requirements of the workpiece. Typically, the focal point must be positioned on the workpiece's surface or at a specific internal location to achieve optimal processing results. The selection of the focal point position directly influences the cut's quality. Placing the focal point near the workpiece's surface yields a higher-quality cut and facilitates the formation of weld seams. Conversely, positioning the focal point inside the workpiece enables the machining of holes and internal structures. Moreover, the focal point's position affects machining speed, with a closer distance between the focal point and the workpiece's surface resulting in faster machining. Conversely, a closer distance between the focal point and the workpiece's interior impacts the machining speed of internal structures. Additionally, the choice of focal point position is influenced by the workpiece's material type and thickness. Different materials and thicknesses necessitate the selection of an appropriate focus position to achieve optimal processing results.

In summary, the relationship between the laser beam's focus position and the workpiece is a critical factor that demands special attention during laser processing. The selection of the focus position must consider the workpiece material, processing requirements, and desired outcomes to achieve high-quality and high-efficiency processing results.

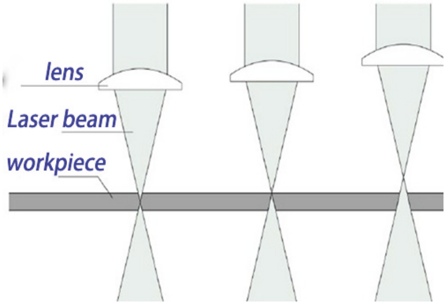

Fig. 1 Schematic diagram of the relationship between the focal point position and the workpiece [6]

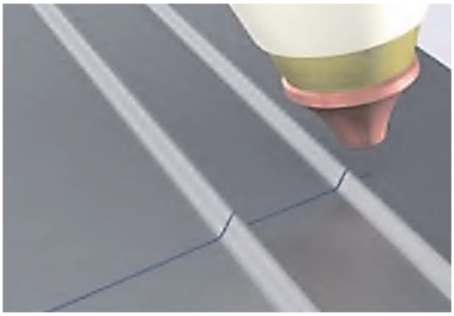

Fig. 2 Dynamic following of the three-dimensional workpiece as its surface undulates.

3.2. *Influence of discrepancies between the part model and actual workpiece geometry*

Discrepancies between the model (CAD model) of the part to be cut and the actual workpiece geometry are a critical concern that demands special attention during the laser cutting process. These discrepancies can arise from various factors, including material properties, processing parameters, and the precision of the laser cutting system.

Thermal effects play a significant role in inducing these discrepancies. The high temperatures generated during the laser cutting process can lead to thermal deformation of the material, resulting in deviations between the actual workpiece geometry and the design dimensions in the CAD model. Furthermore, the molten area produced by laser cutting may cause material shrinkage or deformation, leading to differences between the cutting contour and the dimensions designed in the CAD model. Additionally, the width of the laser beam can impact the cutting contour, potentially resulting in small dimensional discrepancies during fine processing. Moreover, distinct materials exhibit varying coefficients of thermal expansion and melting points, leading to dimensional variations in cut parts across different materials. Mechanical vibrations may also affect machining accuracy, particularly for large-sized parts.

These factors collectively contribute to potential deviations in the actual geometry of the cut part from the design dimensions in the CAD model. To mitigate this effect, precise control of laser cutting processing parameters, optimization of the cutting process, selection of suitable materials, and accurate calibration of the laser cutting system are essential. These measures aim to ensure that the actual processing results closely align with the geometric dimensions designed in the CAD model, minimizing discrepancies to the greatest extent possible.

3.3. *Influence of Workpiece Fixture Positioning*

The positioning accuracy between the laser processing machine and the workpiece fixture can significantly impact the machining process and the finished product's quality.

Positioning errors may compromise machining accuracy by causing the workpiece's position on the laser processing machine to deviate from the expected location, thereby affecting machining precision. Substantial positioning errors can result in workpiece features such as holes and cutting contours deviating from design specifications, ultimately affecting the final product's quality. Moreover, positioning errors can lead to an unstable workpiece position on the fixture, resulting in localized stress concentration and subsequent workpiece deformation. Particularly in laser processing, poor positioning may lead to workpiece damage or deformation.

Furthermore, positioning errors can impede productivity by necessitating frequent adjustments in repetitive positioning of the machining machine. In mass production scenarios, positioning errors can disrupt the consistent processing of batch products, thereby impacting production schedules and delivery times. Additionally, positioning errors pose safety hazards, potentially causing workpieces to dislodge from fixtures, damaging equipment during machining, or resulting in safety issues such as laser radiation or mechanical injuries.

To mitigate the adverse effects of positioning errors, precise calibration of the fixture system, utilization of stable and reliable fixture devices, and stringent control of positioning accuracy during the machining process are essential. These measures ensure stable workpiece positioning in the machining process, facilitating high-quality and high-efficiency laser machining.

3.4. *Cutting Power and Corner Speed Influence*

Laser cutting power and the speed of the laser beam at trajectory corners significantly impact the processing effect and quality of laser cutting. While special paths can be designed for two-dimensional cutting movement, three-dimensional movement is constrained by the spatial movement trajectory and speed change errors of the laser beam, necessitating comprehensive technological optimization to address these challenges effectively.*Effect of Laser Cutting Power*

Higher laser cutting power facilitates faster material melting and cutting, thereby enhancing productivity. Optimal laser power ensures the smoothness and quality of the cut line. Inadequate power may hinder material penetration, while excessive power may lead to over-melting and material deformation. Therefore, the laser power must be reasonably adjusted based on material characteristics and thickness to achieve the best cutting effect.

3.4.2. *Influence of Laser Beam Speed at Trajectory Corners*

The speed of the laser beam at trajectory corners significantly impacts cutting quality and accuracy. Excessive speed may reduce the contact time between the laser beam and the material, affecting cut quality, while insufficient speed may compromise processing quality and productivity. Thoughtful adjustment of the laser beam speed at trajectory corners ensures smooth and precise cutting lines, reducing the roughness of the cutting transition area.

In conclusion, laser cutting power and the speed of the laser beam at trajectory corners are pivotal factors influencing laser cutting processing and quality. Optimizing process parameters to suit different materials and processing requirements is essential for achieving the best laser cutting effect in practical applications.

4. Ways to improve cutting quality

4.1. *Adjustment of the focal point position of the laser beam*

The focal point position (see Figure 1) is the distance from the laser focus to the surface of the workpiece, which directly affects the roughness of the cut surface, the slope and width of the kerf and the adhesion status of the molten residue. If the focus position is too forward, this will make the cut workpiece lower end of the heat absorbed by the increase in cutting speed and auxiliary air pressure under certain circumstances, will lead to the cut material and the slit near the melted material in liquid state in the lower surface flow, after cooling the melted material will be a ball adhering to the workpiece on the lower surface; if the position of the lagging behind, the lower end of the material to be cut by the lower end of the surface of the heat absorbed by the reduced, so that the If the position is lagging, the heat absorbed by the lower surface of the material to be cut is reduced, so that the material in the slit cannot be completely melted, and some sharp residues will be adhered to the lower surface of the plate. Under normal circumstances, the focus position should be on the surface of the workpiece or a little below, but different material requirements are not the same, cutting carbon steel, the focus on the surface of the plate when the cut quality is better; and stainless-steel cutting, the focus should be in the thickness of the plate 1/2 or so when the effect is better.

Laser cutting system is usually equipped with an automatic focusing system, the system can monitor the focus position of the laser beam through the sensor in real time, and according to the unevenness of the surface of the workpiece to automatically adjust the position of the laser head to ensure that the focus position is always in the best state.

After testing, in the case of the same power and speed parameters, changing the height and focus is found to affect the size of the corner burr. However, the actual three-dimensional workpiece cutting process using capacitive height sensors, with a high dynamic response, can be in the production process to control the focus and focusing height is basically in a dynamic stable state, thus greatly reducing the focusing error on the cutting quality of the impact of the burr to reduce or avoid the production of burrs.

4.2. *Elimination of the number of molds and the actual workpiece deviation effects*

The production process of thermoforming parts entails several crucial steps. Initially, the high-strength steel sheet, produced as a specific-profile sheet in an open coil unloading line, is unloaded and then conveyed to the hot stamping and forming line via a transportation system. On the hot stamping and forming line, robots utilize vacuum suction cups to transfer the sheet to the heating furnace. The initial metallurgical structure of the part blank, such as boron steel (e.g., 22MnB5), primarily composed of ferrite and pearlite, is heated to 930-950°C and maintained in the heating furnace, leading to complete austenitization of the sheet's internal structure. The austenitic structure exhibits excellent plasticity and low strength, rendering it highly suitable for the stamping process. Subsequently, the sheet from the heating furnace is rapidly transferred to the hot stamping mold cavity for stamping and forming using robotic clamps. A key distinction between a hot forming die and a cold stamping die lies in the presence of a water-cooling system. During the forming-cooling (quenching) process, the metallurgical structure of the sheet undergoes a complete transformation into fine martensite. The martensitic structure exhibits exceptional strength and hardness, enabling the tensile strength of hot formed parts to reach 1300-2000MPa.

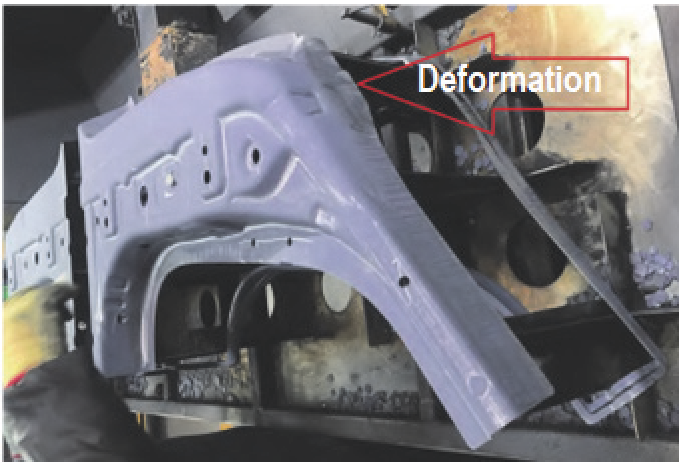

Fig. 3 Dimensional errors caused by deformation of hot stamped formed parts

In the practical hot stamping production process, the stress state undergoes changes as the hot-stamped parts are formed out of the mold due to material phase transitions, uneven cooling, and errors in blank positioning. These factors contribute to varying degrees of stress state changes in the hot-stamped parts, subsequently leading to geometric size alterations. The resulting geometric dimensions of the actual part differ somewhat from those of the original digital model, thereby contributing to the poor quality of corner cuts (refer to Fig. 3) and burns on the part. Upon testing, it was observed that an increase in burrs occurred when the speed remained constant, indicating a change in the quality of corner cuts.

4.3. *Elimination of errors in laser cutting positioning fixtures*

To mitigate the errors arising from laser cutting positioning fixtures, several measures can be implemented. These include the use of precision fixtures with high-precision positioning functions to improve positioning accuracy and ensure secure fixation of the workpiece during the machining process. Additionally, the introduction of a positioning detection system for real-time monitoring of the workpiece's position on the processing machine enables the timely detection and correction of positioning errors. Pre-correction measures can be introduced in the laser processing program based on the positioning error, and software compensation or automatic adjustment of process parameters can be employed to adapt to the positioning error. Furthermore, the establishment of reasonable quality control standards and processes, along with strict inspection of processed products, ensures that the product quality aligns with the specified requirements. By comprehensively implementing these measures, the adverse impact of positioning errors between the laser processing machine and the workpiece fixture can be minimized, leading to improved production efficiency and product quality. Simultaneously, by measuring the geometric dimensions of the same batch of parts, adjusting the laser cutting process, and implementing necessary compensation, the number and size of cutting burrs can be successfully reduced.

4.4. *Elimination of the effects of cutting power and cutting motion corner speeds*

The amount of laser power has a considerable effect on the cutting speed, kerf width, cut thickness and cut quality, as shown in Piece Figure 4. The size of the required power is based on the characteristics of the material and the cutting mechanism. For example, good thermal conductivity and high melting point, as well as cutting materials with high surface reflectivity require a larger amount of laser energy to act on the slit for a longer period of time, which leads to an increase in the slit width. When the speed is too slow, the laser beam action time is too long, the difference between the upper and lower cutting seam of the workpiece will be very large, the quality of the cut will be reduced, and productivity will also be greatly reduced. As the cutting speed increases, the laser beam energy in the workpiece on the role of time becomes shorter, which makes the heat diffusion and heat conduction effect becomes smaller, so that the width of the slit is correspondingly smaller. When the speed is too fast, the workpiece will be cut due to the lack of cutting heat input to cut through the situation, this phenomenon belongs to the incomplete cutting, and the melted material can not be blown off in time, the molten material will make the cut seam re-welding. After testing, it was found that in the case of the same power, change the speed, will affect the size of the corner burr, see Figure 5.

It can be found that in actual production, the variation of parameters such as power and speed has a greater impact on the burr. During the test, a number of different cutting databases can be taken for the same part to determine the cutting process. These different cutting process parameters are applied to test the burrs and burns that occur when the cutting path undergoes a sharp turn. By analyzing cutting defects at the corners of a 3D part, such as the size and density of burrs, cutting parameters can be optimized to reduce burrs. Similarly, burr reduction has the potential to reduce cutting speed and power, and cutting efficiency can be drastically reduced. Complex program setups and operations are also more cumbersome and require excessive levels of operator craftsmanship. Therefore, through research and optimization, the development of specific material and process databases, and the integration of data and operation processes, operation facilitation can be achieved.

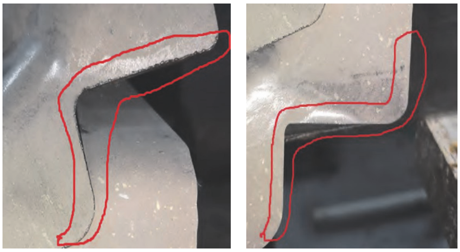

Fig. 4 Comparison of the effect of different corner speeds on burrs.

Fig. 5 Comparison of the effect of different corner speeds on burrs.

Cutting three-dimensional workpiece is not always straight line cutting, in the cutting process there will be a large number of corners, bumps or change of direction, the actual running speed of the machine is constantly changing. For this reason, we have collected real-time path speed, laser power, frequency, duty cycle and other parameter data, according to its changes in the matching of the optimal cutting parameters, to find its corresponding functional relationship, the realization of the output variable will be momentary changes in the parameters kneaded into the machine tool's movement, to achieve the efficiency of the non-decrease in the quality of the cut rise, or a slight decrease in efficiency, the quality of the cut is improved. The formula is written into the system program, and the function can be used by directly activating the function through the human-computer interaction interface.

The laser power and the feed path speed form a function, as shown in Figure 6.Using FCTDEF it is possible to define a third-order polynomial of the form:

$$y=f(x)=a0+a1x+a2x2+a3x3 \quad \text{(Eq. 1)}$$

Example of a straight-line segment polynomial: with an upper limit of 1000 and a lower limit of -1000, the polynomial whose vertical coordinate line segment is a0=$AA_IM[x] and whose slope is 1 is defined as: FCTDEF (1, -1000,1000,$AA_IM[x],1).

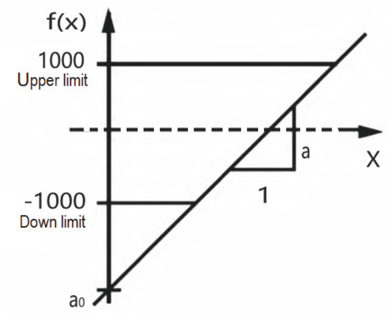

Fig. 6 Predicted linear relationship between speed and power

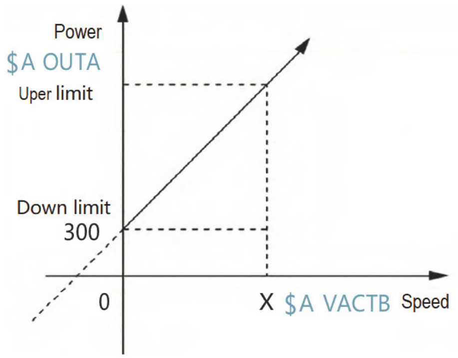

Fig.7 Linear relationship between actual speed and power

According to this polynomial, in laser cutting, the linear segment expression is applied to control the laser power output, and the trajectory speed is used as the basis to control the laser power analog output.

Take 3000W laser as an example, the maximum power of the laser 3000W, so the upper limit value of power output is $A OUTA3000W, in the perforation or speed 0, the laser output power can still cut the material, set the output power at this time $OUTA300W, i.e., the lower limit value of the output power, set the machine tool processing speed X, the actual processing path speed X1, then:

$$a0= (300-0) \times 1=300.$$
$$a1=(3000-300)/(X-0) =2700/X$$
$$a2=a3=0$$

Thus, the power can be known:

$$Y=300+(2700/X) \times X1 \quad \text{(Eq. 2)}$$

can be simplified to

$$Y = a0 + a1 \times X \quad \text{(Eq.3)}$$

At this point, the laser output power Y changes with the speed of the processing path X. Using the tracking function, the laser output power is output at a fixed value when the trimming is not turned on. When the trimming program is turned on, the laser output power is automatically adjusted with the actual path speed (see Fig. 7).

5. Conclusion

The conclusion of the paper outlines the systematic study and analysis of laser processing technology for hot stamping and forming parts made of high-strength steel. The root causes of the laser cutting burr problem have been thoroughly explored from multiple perspectives. Based on the analyzed results, solutions for different factors are proposed, and their effectiveness is verified through field tests. The research findings demonstrate that measures such as adjusting the focus position, optimizing the cutting nozzle type, and modifying the cutting parameters can effectively reduce corner burrs, simplify the part debugging process, and enhance the efficiency of part debugging.

Following the defect analysis and implementation of improvement measures, the cutting defects are significantly reduced, particularly with the corner burr of the part cutting trajectory being reduced by over 80%, effectively addressing the issue of burns on the cut parts. Moreover, the part debugging process is streamlined, and the efficiency of part test cutting and debugging is improved by more than 30%. These integrated solutions, incorporated into the three-dimensional five-axis cutting machine SF3015 and SF4025-CT produced by Huagong Laser, as well as other new large door ring cutting machine process software for high-strength steel hot stamping and forming parts laser processing technology, provide a crucial foundation for quality control. Furthermore, they offer valuable guidance and reference for technical research and engineering practice in related areas, ultimately enhancing the quality of high-strength steel hot stamping and forming parts laser processing. This study holds significant practical importance for improving the quality of laser processing of hot stamping and forming parts made of high-strength steel.

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