

An Intelligent Algorithm for Path Planning and Feed Rate Prediction in Shot Peening Forming of Complex Integral Panels

Chuang Liu

Northwestern Polytechnical University

Xianjie Zhang

zhangx.j@nwpu.edu.cn

Northwestern Polytechnical University

Zhiyong Zhao

Northwestern Polytechnical University

Research Article

Keywords: Shot Peen Forming, Shot Peening Path Planning, Intelligent Prediction of Feed Rate, Knowledge Acquisition, Integral Panel

Posted Date: September 2nd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10663455/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

*An Intelligent Algorithm for Path Planning and Feed Rate Prediction in Shot Peening
Forming of Complex Integral Panels*

Chuang Liu, Xianjie Zhang^{*1}, Zhiyong Zhao

(School of Mechanical Engineering, Shaanxi Engineering Research Center for Digital
Manufacturing Technology, Northwestern Polytechnical University, Xi'an 710072, China)

Abstract:

Shot peen forming process planning for integral panel primarily involves path planning and parameter prediction. The shot peening path of integral panels determines the spatial distribution of shot impacts, while process parameters govern the deformation magnitude at each impact position. Together, these two factors control the shot coverage rate and outer surface accuracy of the component. Within the computational framework for progressive shot peening process parameters, this paper proposes an intelligent algorithm for path planning and process parameter prediction in shot peening forming of complex integral panels. First, the structural characteristics and shot peening forming parameters of complex integral panels are analyzed. Since the spanwise curvature radius of wing integral panels is relatively large, they can be approximated as single-curvature surfaces. A shot peening path calculation method based on extreme curvature tracking and an equal-strength region merging algorithm via feed rate consolidation are established. Subsequently, in accordance with the structural features of integral stiffened panels, test specimens including flat plate, I-shaped stringer and T-shaped stringer specimens are fabricated for shot peening forming experiments. The forming laws of flat plates and stiffened structures are compared and analyzed. The results verify that tests on flat plate specimens can provide fundamental data for the shot peening parameter design of stringer-reinforced integral panel. Further, specimens with a length of 200 mm and a width of 50 mm are prepared, featuring four different base plate thicknesses and two rib thicknesses (6 mm and 8 mm). Shot peening tests are conducted under 11 different feed rates to acquire prediction data for feed rate. Three feed rate prediction models for shot peening forming are established respectively using regression analysis, BP artificial neural network and linear interpolation. Comparative analysis reveals that the linear interpolation method delivers higher prediction accuracy and stability. The proposed methods are adopted to calculate the feed rate at each discrete point along the shot peening path of a practical part. The obtained data is used to compile NC programs and conduct shot peening forming. The results of component forming tests show that the outer surface deviation of the finished workpiece meets the precision requirements.

Key words: Shot Peen Forming; Shot Peening Path Planning; Intelligent Prediction of Feed Rate ; Knowledge Acquisition; Integral Panel

1. Introduction

Wing integral panels are both an important component constituting the aerodynamic shape of aircraft and the primary load-bearing structure of the wing ^[1]. Shot peen forming, as the preferred method for integral panel forming, utilizes high-velocity metal shot streams impacting the surface

¹ Corresponding author. E-mail address: zhangxj@nwpu.edu.cn

of thin metal plate components to generate cumulative local plastic deformation, introducing compressive residual stresses in the surface layer of the component, thereby achieving the required surface curvature^[2]. The key to process design lies in how to inversely determine the optimal set of process parameters from the desired forming profile under the complex structural conditions of variable thickness and variable curvature along the shot peening path of integral panel components^[3].

This problem constitutes a deep theoretical challenge due to the high dimensionality of the parameter space and the multi-level causal chain of the shot peening process: at the microscopic level, the local plastic deformation and compressive residual stress field introduced by each shot impact; at the mesoscopic level, the statistical cumulative effect of millions of shot impacts (coverage); and at the macroscopic level, the structural mechanical response of plate/shell bending deformation. The coupling between shot impact paths and process parameters becomes the core link connecting the physical mechanisms of the process to the final surface accuracy.

The main work of integral panel process planning includes planning the shot peening paths based on the geometric features of the part and calculating the feed rates at each variable-thickness and variable-curvature discrete point, and subsequently generating numerical control programs to drive the shot peen forming equipment. The peening path determines the spatial distribution of shot impacts, while the process parameters determine the magnitude of deformation at each impact location. Chordwise curvature is the key concern in wing panel forming. Path planning algorithms for integral panels mainly include methods based on chordwise equal percentage lines^[4] and panel surface extreme curvature lines^[5]. Narrow strip peening is conducted along the spanwise direction to form chordwise curvature. Nevertheless, none of these approaches take actual peening forming efficiency into account. However, supercritical hyperbolic airfoils are increasingly adopted in wing design of new-generation aircraft. It is necessary to establish a path planning algorithm combining the spatial variation characteristics of curvature and forming efficiency requirements.

Although there is a complex mapping relationship among part structure, material, path parameters and process parameters^[6]. Progressive parameter decoupling provides an operable framework for path planning of complex panels^[7]. In engineering practice, parameters such as spraying distance, spraying angle, shot flow rate, shot size and pre-stress level l are kept constant during the peening process once selected. Spraying air pressure and feed rate are variable process parameters. For instance, integral panels with base thickness below 8 mm can be formed in a free state without pre-stress. Parts with small variations in thickness and curvature radius adopt identical spraying air pressure to reduce the impact of pressure fluctuation on processing efficiency and quality.

feed rate lies at the meso-macro coupling interface of the causal chain of shot peening effect. It directly controls the shot impact density per unit area, namely coverage rate, and further regulates forming curvature via the spatial distribution of residual stress field. Experiments reveal that the correlation among feed rate, coverage rate and curvature is not a simple linear function, but features saturation and threshold effects. Calculation methods for shot peening process parameters include analytical approaches, numerical simulation methods and prediction methods based on experimental data^[8].

The physical essence of shot peening is to alter the mechanical behavior of components by introducing a compressive residual stress layer on the material surface. Analytical formulas quantitatively describe the correlation between feed rate and deformation, such as the relationships

of forming curvature radius with material mechanical properties, thickness, feed rate and pit depth caused by shot impact on the workpiece surface^[9], as well as the correlation between process parameters and shot peening intensity^[10]. Nevertheless, shot peening intensity is a combined effect of air pressure, shot size, spraying distance and other factors, which cannot be determined prior to processing. Hence, such formulas are hardly applicable to the prediction of practical component process parameters.

The complexity of forming mechanism makes it extremely difficult to accurately predict parameters via analytical methods or numerical simulation. Numerical simulation is commonly adopted to forecast the shape and performance of specimens under various parameters^[11,12,13]. However, it is challenging to determine appropriate process parameters for specified target shapes and dimensions^[8]. Machine learning offers a data-driven solution for parameter design. Its core challenges involve data quality, model selection and training, as well as model generalization capability^[3,6].

In terms of prediction model construction, supervised learning serves as the most prevalent machine learning approach. Models are trained with datasets containing inputs and outputs. The algorithm aims to bypass explicit physical intermediate mechanisms and directly establish the mapping from forming profiles to process parameters, so as to generate corresponding outputs based on new inputs^[14]. Major methods cover regression analysis^[7], response surface methodology^[15,16,17], artificial neural networks^[8], as well as their combined applications^[19].

The knowledge-based progressive process parameter calculation method determines constant parameters such as spraying distance and spraying pressure in shot peening through sequential tests, then regression analysis is adopted to fit the relationships between feed rate, curvature radius and part thickness for the calculation of feed rate parameters^[7]. Response surface methodology acquires data via finite element-based tests and constructs second-order response surface equations between residual stress and shot peening parameters^[15,16,17], which optimizes process parameters from the perspective of mechanical performance.

Artificial neural network-based prediction models are the most widely applied^[6]. For instance, neural networks combined with genetic algorithms can establish complex nonlinear correlations between shot peening parameters including air pressure, shot mass flow rate and workpiece feed rate, and mechanical responses such as bending radius, while preventing local optimal solutions^[8]. Deep learning-based process models have been applied to design shot peening forming processes for single-curvature aircraft panels with a curvature radius of 3500 mm, achieving a maximum deformation error below 1 mm^[20]. Despite respective merits, these algorithms lack comparative evaluation on calculation accuracy, and fail to take into account the structural characteristics of integral panels as well as practical requirements for high-efficiency shot peening forming.

In terms of high-quality data acquisition, experiments must be conducted considering the complex structural features of actual integral panels. For the same materials, analogical reasoning based on structural equivalent simplification is commonly adopted to establish the mapping from geometric parameters to process parameters, which deduces process parameters for local part structures using forming data of flat specimens.

Integral panels feature variable curvature and variable thickness, as well as internal structures such as integral reinforcing pads, frames and stringer^[1]. Existing researches mainly focus on test specimens or single-curvature panels^[8,20]. In fact, most integral panels are ribbed structures with double-curvature profiles. Stiffeners improve structural rigidity and greatly reduce shot peening

deformation^[21]. It remains an unsolved fundamental problem to reliably extend local precision to the overall panel scale and realize the theoretical transition from point precision to surface precision.

Quantitative analysis on the forming laws of plate and stringer components is required to obtain accurate process parameter data for practical part prediction, including comparative analysis of forming effects among specimens with different stringer structures, and between stringer and plate specimens. To improve prediction accuracy and intelligence level, an intelligent calculation method with high precision shall be developed through comprehensive comparison based on high-quality data. It can effectively enhance prediction stability and reliability, and lower the workload of manual shaping correction.

Taking actual integral panel parts as research objects, this paper firstly proposes a shot peening path planning algorithm combining initial path planning and equal-strength segment division. The influence rule of part structure on shot peening deformation is analyzed via experiments, providing scientific basis for acquiring process parameter prediction knowledge. Shot peening forming tests with varying thicknesses and feed rates are conducted to obtain process data. Then to calculation of feed rates of discrete path segments, three prediction models for shot peening process parameters are established and compared. The model with superior accuracy is selected for calculation. Finally, parameters of discrete points on each shot peening path of the sample part are calculated and merged into equal-strength sections. Experiments are conducted to verify the accuracy of the designed parameters.

2. Integral Panel Shot Peening Path Planning Algorithm

The structural features and geometric information of the integral panel part are analyzed, and shot peening process parameters are classified. The integral panel consists of a thick plate structure serving as the panel base and various internal structural features attached to the base. Based on the analysis of geometric parameters of the example integral panel part, a shot peen forming path planning algorithm and path equal-strength zone division method are established.

2.1. Structural Characteristics and Parameter Analysis of Integral Panels

This study takes the integral panel part shown in Figure 1 as the research object. The part is made of Al7050-T7451 aluminum alloy with overall dimensions of $2000\text{mm} \times 2000\text{mm}$. Its structural features consist of base panel, stringers, access frames, access covers and reinforced bosses. The base panel is a thick plate defined by outer contour surface, inner surface and other thickened curved surfaces. Serving as the theoretical aerodynamic profile of the aircraft, the outer contour surface acts as the design basis of the integral panel, with gradually varying curvature. The inner surface is constructed based on the outer contour surface and serves as the reference for structural features. The thickness between the inner and outer surfaces is uneven.

Internal structural features mainly include stringers, access frames, access covers and reinforced bosses. Most stringers are perpendicular to the inner surface and modeled referring to the stringer axes on the outer surface, which are divided into constant cross-section and variable cross-section types. Sink structures are applied for assembly lap joint with fixed depth. The access frame is a composite structure comprising holes, grooves, sink areas for access covers and reinforcing bosses that guarantee structural strength and stiffness, facilitating aircraft maintenance and inspection.

Internal reinforcing structures restrain the deformation during shot peening forming. Hence, structural influences on forming shall be fully considered in process parameter design. Since access

frames and sink areas require high surface precision for assembly, protective measures are adopted during shot peening. Accordingly, this paper only analyzes the effect of stringer structures on the shot peening forming process of integral panels.

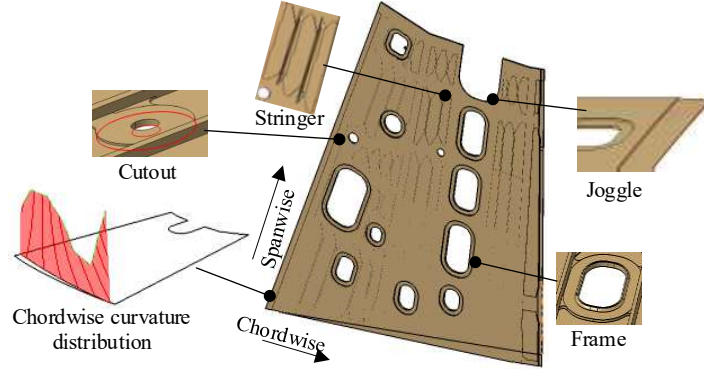


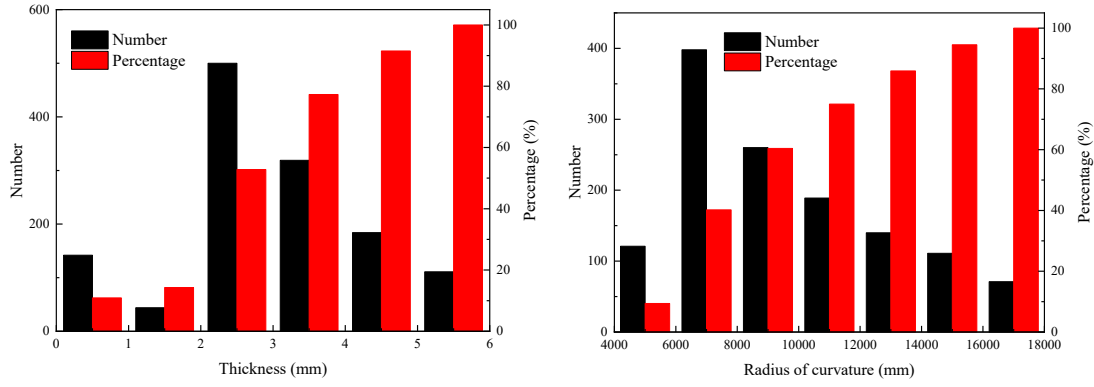
Fig. 1 Structural features of the integral panel part

To obtain the geometric information (thickness and curvature radius) corresponding to the integral panel, discrete points are established by discretizing the integral panel, obtaining the panel thickness and curvature radius corresponding to each discrete point, and using the geometric information at discrete points to characterize the geometric information of the integral panel. Three cross-sectional lines spanning the entire integral panel are selected in both the chordwise and spanwise directions. The cross-sectional lines are discretized at equal intervals, with a discrete distance of 5mm, and the thickness and curvature radius of the integral panel corresponding to each discrete point on the cross-sectional lines are measured.

To acquire geometric parameters including thickness and curvature radius of the integral panel, the panel is discretized to obtain geometric data at discrete points, which represent the overall geometric characteristics. Three cross-section lines crossing the panel are selected along the chordwise and spanwise directions respectively. The lines are evenly discretized with an interval of 5 mm, and the thickness and curvature radius at each discrete point are measured as shown in Figure 2.

(1) Most discrete points feature a thickness ranging from 2 mm to 5 mm, accounting for 76.9% of the total sampling points. Points with thickness between 2 mm and 3 mm take the largest proportion, followed by those within 3 mm to 4 mm, while points in the 1 mm to 2 mm range are the fewest. Zero thickness corresponds to open areas of the panel, and thickness exceeding 5 mm represents reinforced areas of access frames and stringer regions.

(2) Chordwise curvature radius of most points falls within 4000 mm to 16000 mm, occupying 94.5% of all points, with the maximum number distributed from 6000 mm to 8000 mm. Points with spanwise curvature radius over 16000 mm are predominant, and such areas are regarded as flat regions. The minimum curvature radii corresponding to thickness intervals of 0 – 2 mm, 2 – 3 mm, 3 – 4 mm and 4 – 5 mm are 3289.47 mm, 5714.29 mm, 6993 mm and 8620.72 mm respectively.



(a) Thickness distribution

(b) Curvature radius distribution

Fig. 2 Thickness and curvature radius distribution of discrete points on the example part

The shot peening equipment used in this paper is a high-precision, pneumatic MPPF12000 CNC machine, as shown in Figure 3. Compressed air propels the shots through the nozzle to form a shot stream with certain kinetic energy, which impacts the workpiece to produce deformation.

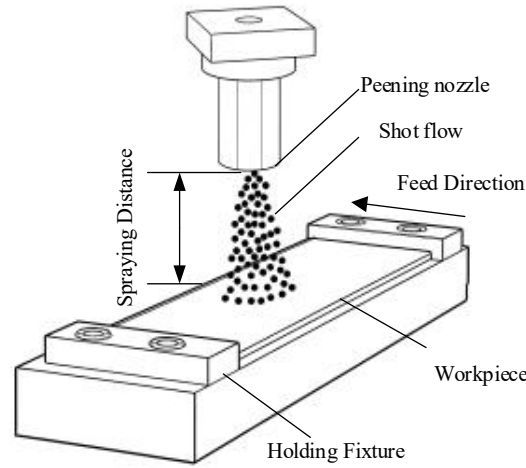


Fig. 3 Schematic diagram of the shot peening process

As shown in Table 1, shot peening process parameters include shot size, spraying angle, spraying distance, shot flow rate, spraying air pressure and workpiece feed rate. In practical shot peening forming applications, shot and nozzles of fixed sizes are generally selected according to actual working conditions, with spraying angle, spraying distance and shot flow rate kept constant. Given that air pressure and shot flow require time to stabilize after adjustment, leading to response lag on the workpiece surface, an optimal air pressure value is determined based on panel geometric dimensions during processing. Only the workpiece feed rate is adjusted to control shot distribution density and coverage rate, so as to regulate its deformation degree.

Table 1 Shot peening process parameters

Process Parameter	Definition
Shot size (mm)	Shot type, including shot material (cast steel, ceramic) and shot size
Spraying angle (°)	Angle between nozzle and workpiece surface
Spraying distance (mm)	Distance between nozzle and workpiece surface
Shot flow rate (kg/min)	Mass of shots ejected from nozzle per unit time

Air pressure (MPa)	Compressed air pressure in shot peening generator
Feed rate (mm/s)	Relative motion speed of nozzle to workpiece

For the integral panel part shown in Figure 1, ASH280 cast steel shots with a diameter of 0.7 mm are adopted in this paper. To enhance impact energy, the spraying angle is set to 90 degrees with the nozzle perpendicular to the workpiece surface, and the spraying distance is fixed at 400 mm. The shot flow rate is 10 kg/min. As shown in Table 2, according to the curvature radius range corresponding to varying part thicknesses, the spraying air pressure is determined as 0.15 MPa^[7]. All above parameters are preset before shot peening forming. The workpiece feed rate is calculated based on geometric parameters such as thickness and curvature radius of discrete path segments to control shot coverage and adjust forming curvature.

Table 2 Forming limit curvature radius at 0.15 MPa

Thickness (mm)	Formable limit curvature radius (mm)	Minimum curvature radius of specimen (mm)
0–2	1200	3289.47
2–3	2800	5714.29
3–4	6700	6993.00
4–5	8300	8620.72

2.2. Initial Shot Peening Path Planning Algorithm for Integral Panel

The outer contour surface of integral panel parts derives from aerodynamic shape of wings and is generally a doubly-curved surface. As shown in Figure 4, the curvature at each point on the surface consists of two principal curvatures, namely maximum and minimum curvatures, whose directions are perpendicular or form a certain angle. The direction of maximum curvature is roughly consistent with the chordwise profile.

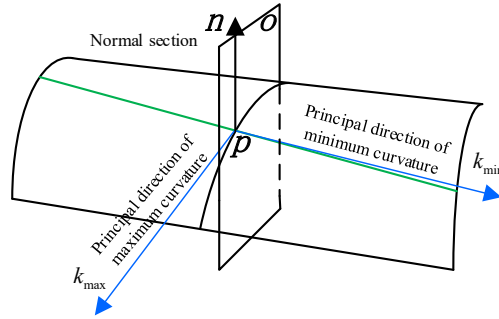


Fig. 4 Schematic of surface curvature lines and bending directions

Theoretically, the target curved surface can be formed as long as two principal curvatures at each point on the outer surface of the panel are achieved. Accordingly, peening paths are divided into chordwise and spanwise shot peening paths to form corresponding curvatures respectively. The spanwise curvature of the studied part is extremely small and can be regarded as flat surface, so the shot peening forming mainly focuses on chordwise path analysis and curvature forming.

A typical wing profile can be defined as a parametric surface S in three-dimensional Euclidean space, which is generally expressed as:

$$\mathbf{r} = \mathbf{r}(u, v) \quad (1)$$

Assume that $\mathbf{r}(u, v)$ has continuous second-order partial derivatives $\mathbf{r}_{uu}$, $\mathbf{r}_{uv}$, $\mathbf{r}_{vv}$. The unit normal vector of surface S at any point is defined as $\mathbf{n}$. This parametric surface characterizes

the outer profile of the formed panel part.

The shot peening path of the integral panel is designated as the extreme curvature line of surface S. The solution of extreme curvature at any point on surface S is defined as:

$$(EG - F^2)k_n^2 - (EN - 2FM + GL)k_n + LN - M^2 = 0 \quad (2)$$

where the coefficients of $E = \mathbf{r}_u^2$ 、 $F = \mathbf{r}_u \mathbf{r}_v$ 、 $G = \mathbf{r}_v^2$ are the first fundamental quantities of the surface in differential geometry, and $L = \mathbf{n} \mathbf{r}_{uu}$ 、 $M = \mathbf{n} \mathbf{r}_{uv}$ 、 $N = \mathbf{n} \mathbf{r}_{vv}$ are the second fundamental quantities of the surface, which are constants at a given point. The two roots of Equation (2) represent the maximum and minimum values of normal curvature at any point on the surface.

The peening path direction is defined as the direction where k_n reaches its extreme value, as shown in Equation (3):

$$(EM - FL)t^2 + (EN - GL)t + FN - GM = 0 \quad (3)$$

The two roots t_1 and t_2 of Equation (3) represent the directions corresponding to the extreme values of normal curvature at any point on the surface.

The forming direction of the integral panel studied in this paper is chordwise. Accordingly, path planning is only conducted along the minimum curvature radius direction in the spanwise direction of the outer surface. A tracing algorithm is established to discretize the integral panel along extreme curvature lines and obtain the shot peening paths.

The boundary lines on the outer surface are selected and evenly discretized. Geometric information including coordinates (x_{uv}, y_{uv}, z_{uv}) , maximum curvature $\rho_{uv}^{\max}$ and its principal direction $\vec{K}_{uv}^{\max}$, minimum curvature $\rho_{uv}^{\min}$ and its principal direction $\vec{K}_{uv}^{\min}$ is extracted from discrete boundary point P_{uv} in the CAD model. The generation procedures of minimum curvature lines are presented as follows: (1) Extract the principal direction $\vec{K}_{0j}^{\max}$ of minimum curvature at the starting point P_{0j} . (2) Calculate the coordinate (x_{1v}, y_{1v}, z_{1v}) of subsequent points P_{1v} via the formula $P_{1v} - P_{0j} = \text{step} * \vec{K}_{0j}^{\min}$ and acquire the local minimum curvature principal direction $\vec{K}_{1j}^{\min}$, where step denotes the tracing interval, and step size is 3mm. (3) Repeat step (2) to acquire successive points along the minimum curvature direction until the coordinates exceed the boundary of the outer surface.

The shot peening paths obtained by tracing minimum curvature lines of the sample part are illustrated in Figure 5.

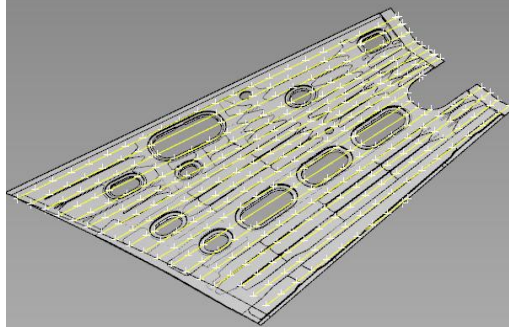


Fig. 5 Shot peening path planning results for the example part

2.3. Equal-strength Region Division Method for Shot Peening Paths

If the machine tool performs shot peening according to the position coordinates and process parameters of each discrete point, frequent adjustment of feed rate caused by numerous points will reduce machining efficiency. Hence, discrete points on each path need to be divided into several equal-strength regions. Such regions share identical shot peening parameters, which can achieve consistent forming effects.

Starting from the initial point of each path, discrete points with similar feed rate are averaged and merged into equal-strength regions. The division process of a single path is shown in Figure 6. The first discrete point is set as the starting position of the initial region. Traverse each discrete point on the shot peening path in sequence until the ratio of the feed rate difference between the u_j -th point and the first point to the average feed rate from the first to the u_j -th point exceeds the threshold ΔV , as shown in Equation (4).

$$e_j = u_j |V_1 - V_{u_j}| / \left(\sum_{k=1}^{u_j} V_k \right) \quad (4)$$

Take the u_j -th discrete point as the end of the first equal-strength region. The feed rate of this region is represented by the average value of feed rates of all discrete points within the region, as shown in Equation (5).

$$\bar{V}_j = \frac{1}{u_j} \left(\sum_{k=1}^{u_j} V_k \right) \quad (5)$$

Following this rule, the path is sequentially divided into equal-strength regions, and the feed rate of each equal-strength region is calculated.

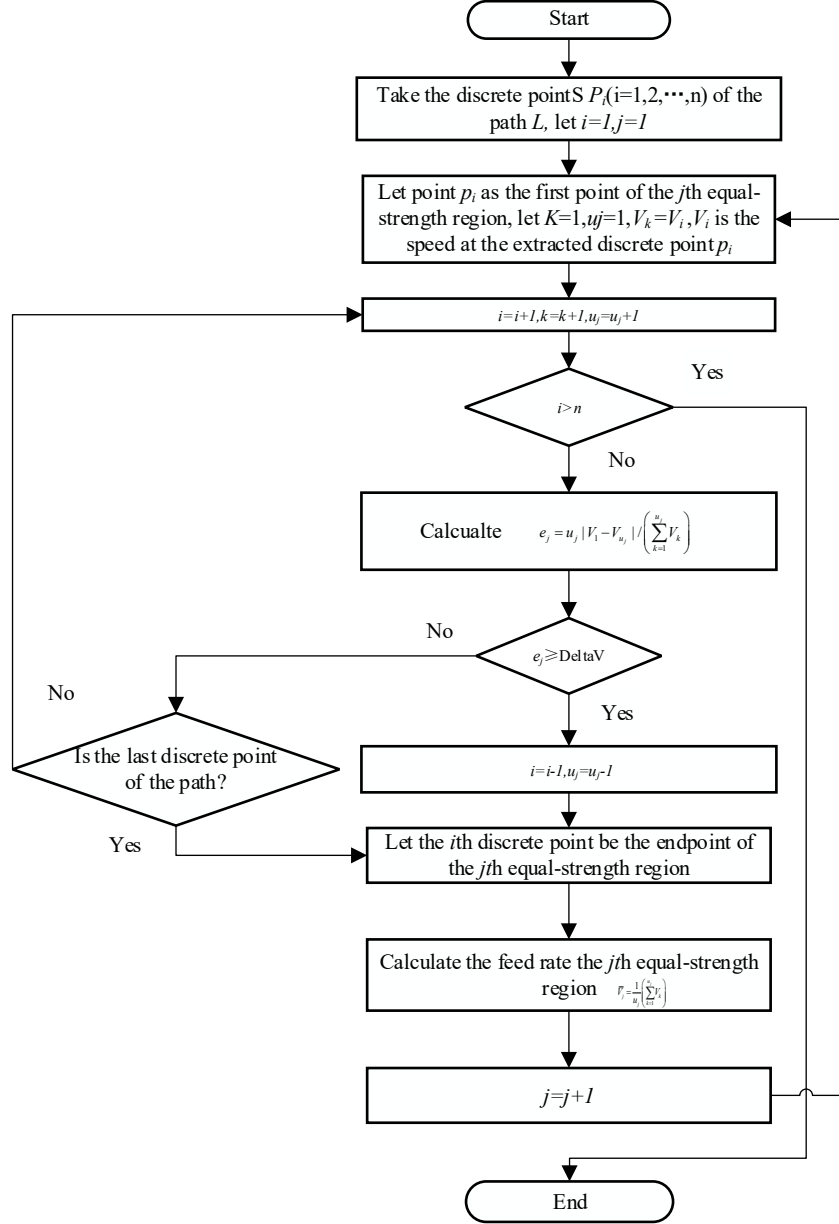


Fig. 6 Flow chart of equal-strength zone division for peening path discrete point

3. Knowledge Acquisition for feed rate Parameter Prediction of Stringer-Reinforced Integral Panels

To accurately calculate the feed rate at each location along the integral panel's peening paths, the influence of stringer structures on forming must be considered and an appropriate feed rate calculation model must be established. Shot peen forming experiments are conducted by varying the machine feed rate to form specimens with different structures under selected peening process parameters. The acquired forming data are used to establish the integral panel shot peening process parameter prediction algorithm.

3.1. Influence of Stringer Structures on Shot Peen Forming

To verify the forming laws of flat plates and different stringer structures, forming experiments were conducted under the spraying pressure of 0.15 MPa. The adopted feed rates were 65 mm/s,

84.5 mm/s, 109.9 mm/s, 142.8 mm/s, 185.6 mm/s and 241.3 mm/s. Specimens included flat plates, T-shaped and I-shaped ribbed parts with a base dimension of 400 mm $\times$ 138 mm and three base thicknesses of 2 mm, 3 mm and 4 mm, as listed in Table 3. The geometric parameters of stringer structures are presented in Figure 7.

Table 3 Experimental grouping

Base dimensions (mm ³)	Specimen structure	Shot spec.	Air pressure (MPa)	Shot flow (kg/min)	Feed rate (mm/s)
	I-shaped				65
400 $\times$ 138 $\times$ 2	stringer /T-				84.5
400 $\times$ 138 $\times$ 3	shaped	ASH280	0.15	10	109.9
400 $\times$ 138 $\times$ 4	stringer /				142.8
	Flat plate				185.6
					241.3

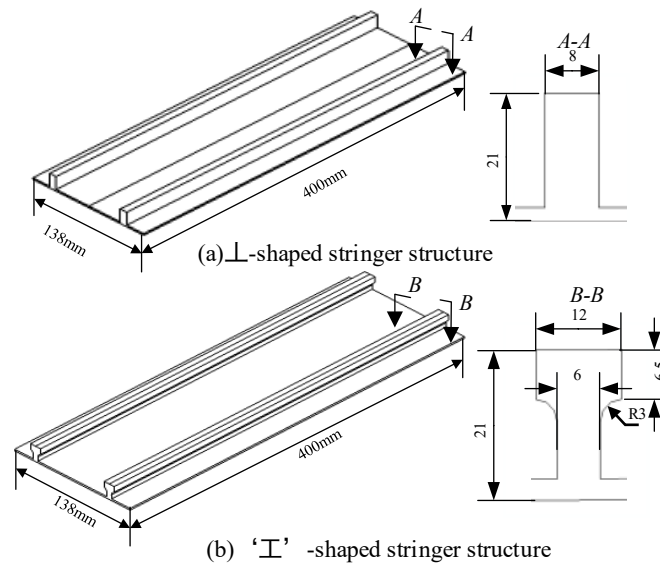


Fig. 7 L-shaped and I-shaped double-stringer structural parameters

To ensure the accuracy and reliability of forming data, two shot peening tests are conducted for each parameter condition, requiring a total of 108 specimens. The shot peening process is implemented along the center of stringers. The formed specimens of ribbed parts are shown in Figure 8.

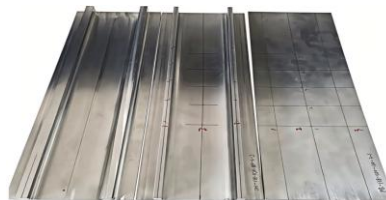


Fig. 8 I-shaped, T-shaped double-stringer structures and flat plate formed specimen

The average curvature radius of multiple regions along the path is taken as the forming curvature radius of specimens, and the analytical results are shown in Figure 9. Under identical thickness and feed rate, the forming curvature radius of T-shaped components is larger than that of

I-shaped ones. The stringer thickness of all I-shaped parts is 8 mm. For T-shaped parts, the stringer thickness reaches 12 mm at the top and reduces to 6 mm at the junction with the base plate. Such structure delivers lower overall deformation resistance and superior forming performance compared with 8 mm-thick I-shaped components.

Flat plates feature uniform and symmetrical cross-sections and produce spherical deformation with bidirectional curvature. By contrast, stringers in reinforced components restrict uniform in-plane deformation, making strain release in the form of bending deflection. The I-shaped structure with an overall stringer thickness of 8 mm imposes strong resistance to deformation. Consequently, flat specimens and 8 mm-thick I-shaped reinforced parts exhibit similar curvature radius. The maximum curvature radius deviation among the three types of specimens is 139.6 mm, occurring at a base thickness of 3 mm and machine feed rate of 185.6 mm/s, with a forming deviation of 3.9%. For the studied integral panel part, most curvature radius fall within 6000 mm to 8000 mm. Taking the curvature radius of 7000 mm and arc length of 1000 mm for calculation, the profile deviation namely chord height deviation is approximately 0.52 mm, basically meeting the requirement that profile deviation shall be controlled within 0.5 mm.

Accordingly, for integral reinforced panels with rib thickness below 8 mm, the constraint effect of stringers on chordwise forming can be neglected. Flat plates can serve as equivalent structures of T-shaped and I-shaped reinforced components for shot peening parameter calculation.

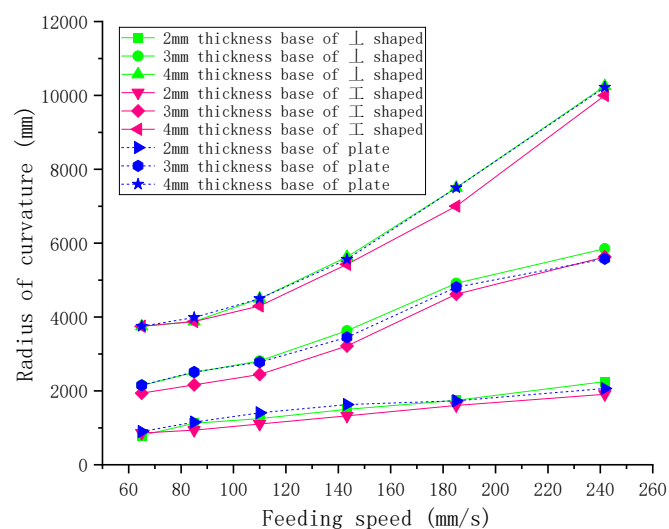


Fig. 9 Forming results of three types of structural specimens

3.2. Knowledge Acquisition for feed rate Calculation in Shot Peening Forming

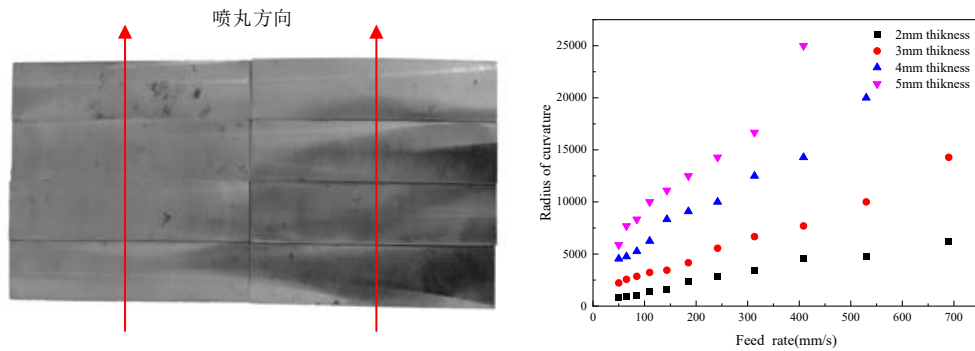
Forming tests were conducted on Al7050-T7451 flat specimens with different thicknesses and an aspect ratio of 4:1 under various feed rates, to acquire data for establishing the feed rate calculation model. As shown in Table 4, the specimens are 200 mm in length and 50 mm in width, with four thickness specifications of 2 mm, 3 mm, 4 mm and 5 mm.

A series of feed rates including 50 mm/s, 65 mm/s, 84.5 mm/s, 109.9 mm/s, 142.8 mm/s, 185.6 mm/s, 241.3 mm/s, 314.1 mm/s, 408.3 mm/s, 530.8 mm/s and 690 mm/s were adopted for the forming experiments. Two repeated tests were carried out for each parameter group to guarantee the accuracy and reliability of experimental data, and a total of 88 specimens were used.

Table 4 Flat plate specimen experimental grouping

Specimen dimensions (mm ³)	Shot size	Air pressure (MPa)	Shot flow (kg/min)	Feed rate (mm/s)
200×50×2 200×50×3 200×50×4 200×50×5	ASH280	0.15	10	50
				65
				84.5
				109.9
				142.8
				185.6
				241.3
				314.1
				408.3
				530.8
				690

The formed flat specimens are displayed in Figure 10(a). Their curvature radius are measured via 3D laser scanning, and the measured results under different thicknesses and feed rates are presented in Figure 10(b). The forming curvature radius rises and deformation declines with the increase of machine feed rate and specimen thickness. Higher feed rate reduces shot coverage on the specimen surface and weakens acting force. At a fixed feed rate, thicker specimens possess stronger deformation resistance, leading to decreased deformation.



(a) Formed flat plate specimens (b) Forming curvature radius measurement results

Fig. 10 Forming results of flat plate specimens with different thicknesses at different feed rates

The forming test data records the curvature radius of specimens, including specimen code, material grade and temper state, geometric dimensions such as length, width and thickness, shot peening parameters involving injection pressure, shot size, spraying angle, shot flow rate and feed rate, as well as forming curvature radius. An integral panel shot peening knowledge management system is developed to store specimen parameters and forming data. The measured curvature data of specimens with diverse structures are converted into knowledge storage, supporting the establishment of intelligent prediction algorithm for shot peening feed rate.

4. Prediction Model for Feed Rate at Discrete Points on Integral Panel Shot Peening Path

The above forming test data are applied to construct the feed rate calculation model for integral panel shot peening. Regression analysis, BP artificial neural network and linear interpolation are adopted respectively to establish computational methods. The feed rate of peened workpiece is

calculated based on geometric information corresponding to shot peening paths, and the algorithm with optimal accuracy is selected finally.

4.1. Feed Rate Prediction Method Based on Multiple Regression Analysis

Regression analysis establishes regression equations between independent and dependent variables by analyzing their correlation, and predicts dependent variable values corresponding to varying independent variables. The linear regression model applies to simple linear relationships. It formulates correlations between single or multiple independent variables and dependent variables, and solves relevant coefficients via the least square method. As a fundamental and widely adopted prediction approach, regression analysis is commonly used in practical research.

This method is adopted to fit the relationship among thickness, feed rate and curvature radius. According to the test results in Figure 10, forming curvature radius rises monotonously with feed rate and specimen thickness. Hence, the relational expression can be defined as:

$$R = KT^iV^n \quad (6)$$

where: R — forming curvature radius (mm); T — specimen thickness (mm); V — machine feed rate (mm/s).

Logarithmic transformation is performed on both sides of Equation (6) to convert it into a linear equation. Binary linear regression is adopted based on test data to derive the correlation among machine feed rate, specimen thickness and curvature radius, as expressed in Equation (7). The feed rate at discrete points can be calculated according to local thickness and curvature radius[7].

$$V = \left(\frac{R}{14.45T^{2.0241}} \right)^{\frac{1}{0.6914}} \quad (7)$$

4.2. feed rate Prediction Method Based on BP Artificial Neural Network

BP artificial neural network adopts the error back propagation learning algorithm. It evaluates the error between the output layer and the previous layer by calculating the deviation between predicted and actual values, and further deduces errors of preceding layers. The weights and thresholds of each layer are adjusted to reduce output errors, and iterative optimization is conducted to achieve expected prediction performance.

A BP neural network consists of input layer, hidden layer and output layer. The three-layer feedforward neural network can approximate arbitrary functions and their derivatives with high precision. Accordingly, this structure is adopted to effectively reduce model complexity while ensuring prediction accuracy.

Main influencing factors on feed rate are divided into material properties and geometric parameters. Input parameters include elastic modulus, yield strength and strain hardening index, as well as structural thickness, curvature radius and rib thickness. The quantity relation between neurons of hidden layer and input layer satisfies the approximate formula:

$$J = 2 * I + 1 \quad (8)$$

The topological structure of BP neural network for feed rate prediction at discrete points on integral panel shot peening paths is shown in Figure 11. There are six neurons in the input layer, representing curvature radius R , part thickness H , rib thickness T , elastic modulus E , yield strength σ_s and strain hardening index n . The hidden layer contains 13 neurons, and the output layer

outputs feed rate V .

For the research object, the material keeps constant. Parameters of flat plates can be directly adopted for panels with stringer thickness less than 8 mm. Practically, only curvature radius and local part thickness at discrete points change.

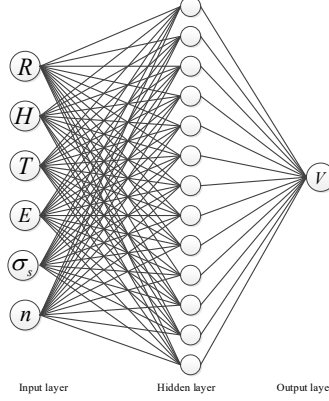


Fig. 11 BP Artificial neural network structure

The transfer functions between input layer and hidden layer, hidden layer and output layer are tansig and logsig respectively, as shown in Equation (9) and Equation (10).

$$\tan sig(x) = \frac{2}{1 + e^{-2x}} - 1 \quad (9)$$

$$\log sig(x) = \frac{1}{1 + e^{-x}} \quad (10)$$

From the experimental data, 74 groups of test data are selected as training samples and 14 groups as test samples. The training samples cover the maximum and minimum values of input parameters. The training function is set as trainlm, and the network training results are presented in Figure 12. The average error between predicted and experimental values is 7.9% for training samples and 10.8% for test samples.

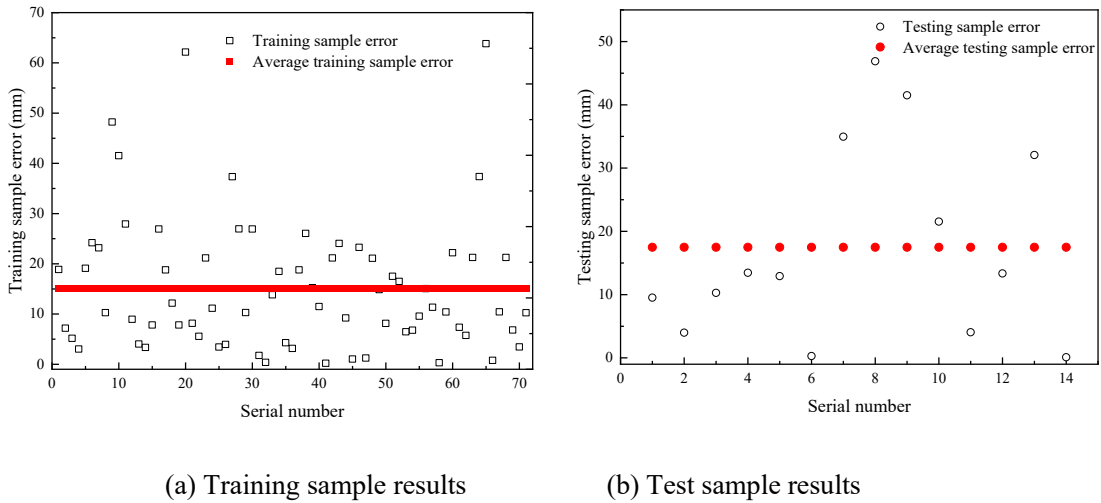


Fig. 12 BP artificial neural network training results

To apply the trained neural network model to shot peening parameter calculation, mathematical expressions are established as follows:

(1) Calculate output values of hidden layer neurons

Let the input and output of the j -th neuron in the hidden layer be h_j and H_j respectively.

x_i ($i=1,2,\dots,6$) denotes network input value, w_{ij} represents the weight connecting the i -th input neuron to the j -th hidden neuron, and θ_j is the threshold of the j -th hidden neuron. The hidden layer adopts tansig transfer function, and its output calculation formulas are shown in Equation (11) and Equation (12).

$$h_j = \sum_{i=1}^6 w_{ij} \cdot x_i + \theta_j \quad (11)$$

$$H_j = \frac{2}{1 + e^{-2h_j}} - 1 \quad (12)$$

(2) Calculation of neural network output value

The calculation method is similar to that of hidden layer. Let o be the input and O be the output of output layer. w_j stands for the weight from the j -th hidden neuron to output neuron, and γ denotes the output layer threshold. Logsig function is used as output transfer function. The output formulas of BP neural network are presented in Equation (13) and Equation (14).

$$o = \sum_{j=1}^{13} w_j \cdot H_j + \gamma \quad (13)$$

$$O = \frac{1}{1 + e^{-o}} \quad (14)$$

4.3. Feed Rate Prediction Method Based on Linear Interpolation

Linear interpolation is conducted on curvature radius and thickness of integral panels based on basic test data to calculate the corresponding machine feed rate. Boundary values adjacent to actual geometric parameters are selected from experimental data to obtain the predicted feed rate. The calculation process is shown in Figure 13.

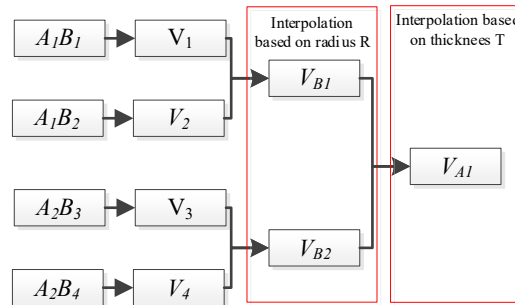


Fig. 13 Interpolation process

The prediction procedures are as follows:

(1) Denote the thickness T and curvature radius R of each panel region by symbol A and B .

(2) Select two thickness levels A_1, A_2 ($A_1 < A < A_2$) close to the actual thickness T . Meanwhile, choose two groups of radius levels B_1, B_2 ($B_1 < B < B_2$) and B_3, B_4 ($B_3 < B < B_4$) matching the curvature

radius R . Four combinations are formed with corresponding feed rates: V_1 for A_1B_1 , V_2 for A_1B_2 , V_3 for A_2B_2 and V_4 for A_2B_1 .

(3) Implement linear interpolation on thickness and curvature radius to work out the feed rate corresponding to actual T and R .

Interpolate V_1 to V_4 according to curvature radius R to obtain V_{B_1} and V_{B_2} . The interpolation formulas are presented in Equation (15) to Equation (18).

$$\frac{B_1 - B}{B_2 - B} = \frac{V_1 - V_{B_1}}{V_2 - V_{B_1}} \quad (15)$$

$$V_{B_1} = \frac{(B_1 - B)V_2 - (B_2 - B)V_1}{B_1 - B_2} \quad (16)$$

$$\frac{B_3 - B}{B_4 - B} = \frac{V_3 - V_{B_2}}{V_4 - V_{B_2}} \quad (17)$$

$$V_{B_2} = \frac{(B_3 - B)V_4 - (B_4 - B)V_3}{B_3 - B_4} \quad (18)$$

Interpolating V_{B_1} and V_{B_2} by thickness T yields V_{A_1} , with the process shown in Equations (19) and (20).

$$\frac{A_1 - A}{A_2 - A} = \frac{V_{B_1} - V_{A_1}}{V_{B_2} - V_{A_1}} \quad (19)$$

$$V_{A_1} = \frac{(A_1 - A)V_{B_2} - (A_2 - A)V_{B_1}}{A_1 - A_2} \quad (20)$$

Substitute V_{B_1} and V_{B_2} into the formula of V_{A_1} , and the final interpolation result is shown in Equation (21).

$$V_{A_1} = \frac{\left\{ (B_1 - B_2)(A_1 - A)[(B_3 - B)V_4 - (B_4 - B)V_3] - \right.}{(A_1 - A_2)(B_1 - B_2)(B_3 - B_4)} \left. \left\{ (B_3 - B_4)(A_2 - A)[(B_1 - B)V_2 - (B_2 - B)V_1] \right\} \right\} \quad (21)$$

4.4. Comparison and Selection of feed rate Prediction Methods

The three aforementioned algorithms are adopted to calculate feed rates at 34 uniformly distributed discrete points, with panel thickness ranging from 3 mm to 5 mm and curvature radius from 7000 mm to 9000 mm. The calculation results are illustrated in Figure 14.

Within the thickness range of 4 mm to 5 mm, the results of the three methods are basically consistent. The deviation between BP neural network and linear interpolation is 1.3%, while that between regression analysis and linear interpolation is 3.9%. Obvious discrepancies appear in the 3 mm to 4 mm thickness interval, with deviations reaching 7.2% and 9.2% respectively.

Linear interpolation delivers steady and mild varying results yet suffers poor scalability, failing to predict data beyond the experimental scope. The neural network method shows noticeable fluctuation between 3.5 mm and 4 mm, and regression analysis presents an inflection point at 4 mm. Consequently, linear interpolation is selected to calculate feed rate at discrete points on shot peening paths of integral panels.

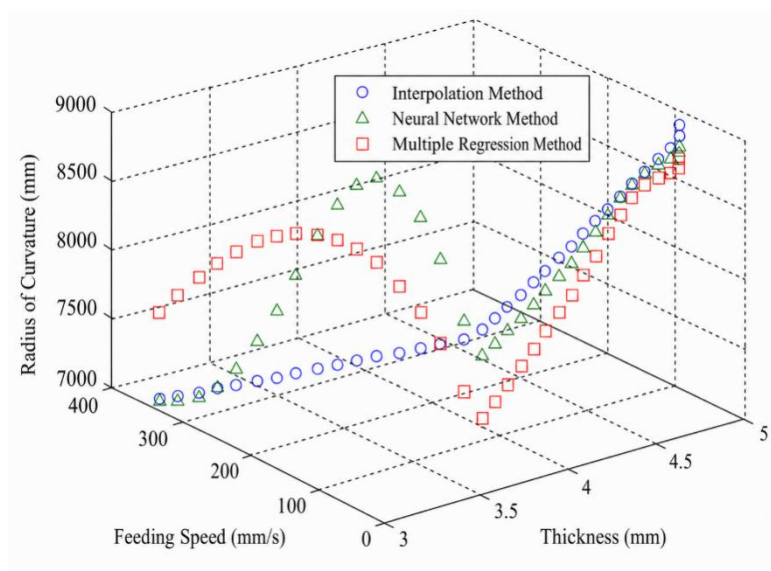


Fig. 14 Comparative analysis of three shot peen forming feed rate prediction algorithms

5. Verification of Actual Part and Analysis

The proposed feed rate prediction method based on linear interpolation is applied to calculate shot peening parameters for practical integral panel parts. Discrete points on peening paths are merged and adjusted to improve forming efficiency. Corresponding NC machining codes are subsequently generated. Numerical shot peening forming experiments are carried out, and the formed workpiece is compared with the design model to analyze forming precision, so as to verify the accuracy of the presented method.

5.1. Feed Rate Calculation

Based on the inner surface, outer surface and chordwise boundary lines of the integral panel design model, discrete points including coordinates, thickness and curvature radius on the shot peening path of outer surface are calculated via extremum curvature tracking method. The outer surface is unfolded and the peening path is mapped onto the unfolded plane, as shown in Figure 15.

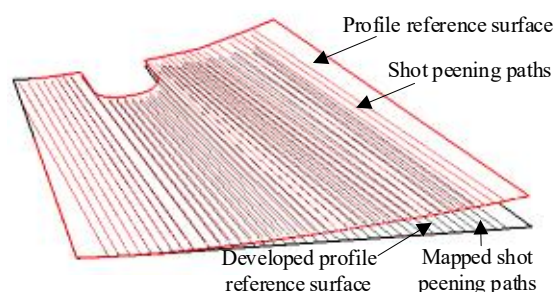


Fig. 15 Shot peening paths for the example integral panel part

Relevant parameters including spraying pressure, shot flow rate and spraying angle are determined. The feed rate is calculated according to the thickness and curvature radius of discrete points. All discrete points on the shot peening path are merged with the threshold for equal-strength

region division set to 5% of the average feed rate, and equal-strength regions together with their corresponding average feed rates are finally formed, as shown in Figure 16.

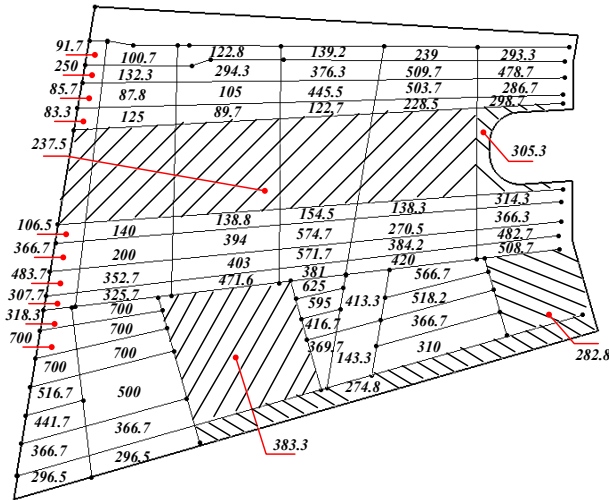


Fig. 16 Process parameters for the example integral panel part

Taking typical paths of ribbed regions on integral panels as examples, the feed rates of corresponding discrete points are calculated. The distributions of thickness, curvature radius and calculated feed rate are presented in Figure 17. The adjustment times of machine feed rate during peening are reduced from 39 to 7, and the forming efficiency is improved accordingly.

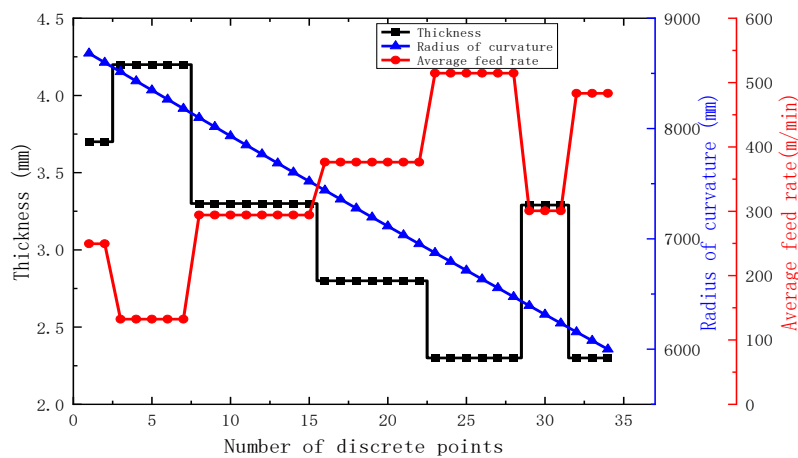


Fig. 17 Thickness, curvature radius, and corresponding feed rate distribution at discrete points in the stringer-reinforced panel zone

Coordinate values of equal-strength paths and shot peening parameters are extracted, and the NC codes for integral panel peening are outputted. The format of generated numerical control instructions is shown in Figure 18.

!喷射气压: 1.5 Bar
!弹丸流量: 10.0 kg/min
!喷射角度: 90.0°
!喷射距: 400.0 mm
!喷嘴直径: 10.0 mm
!弹丸裕度: 90.0%

//////////This is information of numerical control program

!右区域数控指令 Feed rate
!路径编号: 1 Moving position coordinates
workspeed.v.tcp:=400.0;
MoveL Offs(strip1_1,-1106.7,-2102.8,0),workspeed,z0,two_straight_nozzle_1\WObj:=Table_1;
workspeed.v.tcp:=360.3;
MoveL Offs(strip1_1,-1213.6,-1701.7,0),workspeed,z0,two_straight_nozzle_1\WObj:=Table_1;
!路径编号: 2
workspeed.v.tcp:=400.0;
MoveL Offs(strip1_1,-1179.6,-1683.9,0),workspeed,z0,two_straight_nozzle_1\WObj:=Table_1;
workspeed.v.tcp:=746.1;
MoveL Offs(strip1_1,-1086.5,-2037.7,0),workspeed,z0,two_straight_nozzle_1\WObj:=Table_1;
workspeed.v.tcp:=280.6;
MoveL Offs(strip1_1,-1037.1,-2231.6,0),workspeed,z0,two_straight_nozzle_1\WObj:=Table_1;
workspeed.v.tcp:=738.4;
MoveL Offs(strip1_1,-1024.9,-2280.0,0),workspeed,z0,two_straight_nozzle_1\WObj:=Table_1;
workspeed.v.tcp:=174.7;
MoveL Offs(strip1_1,-1012.7,-2328.5,0),workspeed,z0,two_straight_nozzle_1\WObj:=Table_1;

Fig. 18 CNC commands for the example integral panel part

5.2. Analysis of Shot Peening Forming Results

The shot peening forming process of integral panel is shown in Figure 19. A series of pre-processing preparations are required before operation:

- (1) Inspect the status of panel blank.
- (2) Protect non-peening areas. Reference surfaces such as window frames and lap zones on outer surface are covered with protective adhesive tape.
- (3) Verify that spraying angle, shot specification and other equipment parameters conform to technological settings.

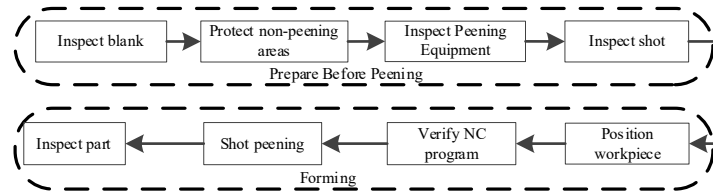
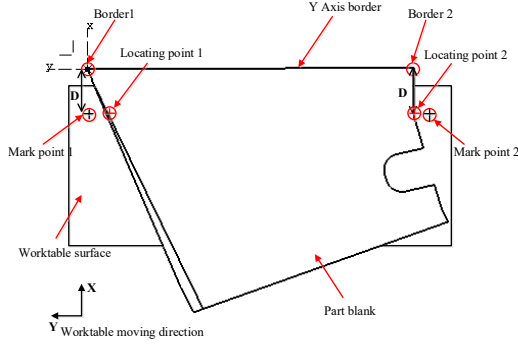


Fig. 19 Shot peen forming process for the example integral panel part

The integral panel blank is accurately positioned on the workbench, as shown in Figure 20(a). The shot peening NC program is activated, and the machine motion mode is switched to relative coordinate operation. Idle running along the programmed path is performed to verify the nozzle trajectory. The access and retract modes of the nozzle are adjusted accordingly. Shot peening is then conducted, and the finished part is displayed in Figure 20(b).



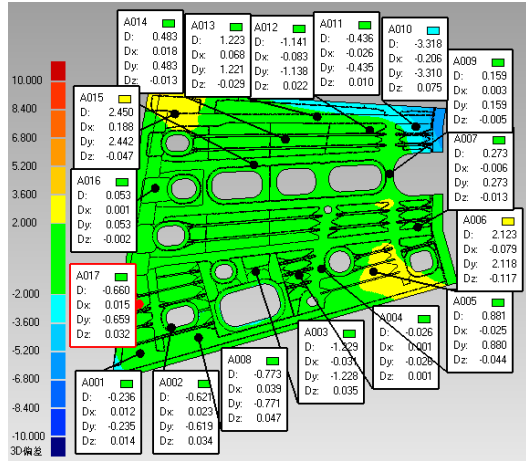
(a) Blank part positioning



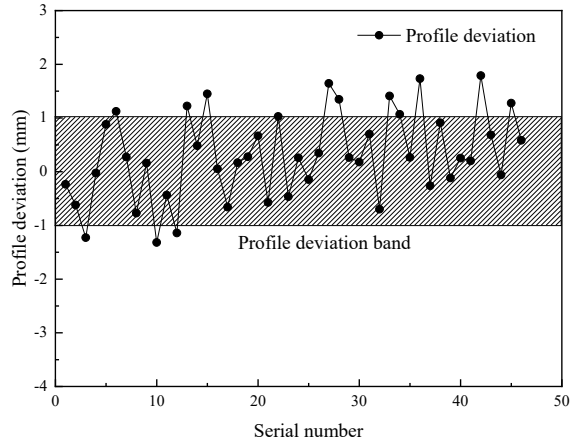
(b) Formed part

Fig. 20 Shot peen forming positioning and formed part

After forming, the inner surface of the part is scanned by Handyscan500 3D laser scanner without applying external force to acquire the point cloud model. The inner curved surface of the design model is imported into Geomagic Qualify for alignment. The deviation between point cloud and design model is shown in Figure 21. The average overall deviation is within ± 1.0 mm.



(a) 3D scan point cloud comparison



(b) Measurement point profile deviation

Fig. 21 Deviation measurement for the example integral panel parts

Assembly areas such as window frames and lap joints are protected during shot peening, resulting in minor deformation and relatively large deviation. The formed panel is placed on a dedicated inspection fixture for surface profile detection. Force-assisted inspection is permitted, with 30 N sandbags placed every 300 mm or 50 N sandbags every 1000 mm. The gap between the part and fixture is less than 0.5 mm, which meets the forming requirements of integral panels.

6. Conclusions

As critical components of aircraft structures, the efficient and high-precision manufacturing of integral panels is dominated by the efficiency and accuracy of process data definition for shot peening forming controlled by driving equipment. In this paper, the chordwise shot peening forming of integral panels under natural conditions is taken as the research object. Intelligent prediction algorithms for feed rate suitable for engineering applications are established, and the accuracy of predicted results is verified through experimental tests.

(1) Doubly-curved integral panels with spanwise curvature radius larger than 16000 mm can be regarded as single-curvature components, which are mainly formed along the chordwise direction.

According to the forming characteristics of flat panels and ribbed panel units, it is found that T-shaped and I-shaped ribs can inhibit the chordwise forming performance of structures. For stringer structures with a stringer thickness less than 8 mm, the chordwise forming deviation between stringer panels and flat panels is less than 0.5 mm/m. Therefore, flat panels can be adopted as equivalent structures of T-shaped and I-shaped ribbed panels to calculate the feed rate for shot peening.

(2) A shot peening path planning algorithm based on extremum curvature tracking is proposed. The chordwise shot peening paths are obtained by tracking the minimum curvature lines. Furthermore, an equal-strength region merging algorithm is developed based on the feed rate distribution of discrete points on shot peening paths. For the tested component, the adjustment times of machine feed rate for a single peening path are reduced from 39 to 7, which greatly improves the efficiency of the shot peening forming process.

(3) Based on experimental data of flat panels with 4 types of thicknesses under 11 groups of feed rates, three feed rate prediction methods including multiple linear regression, BP artificial neural network and linear interpolation are constructed for discrete points on shot peening paths. The results indicate that the multiple linear regression and neural network algorithms exhibit obvious data fluctuations, while the linear interpolation algorithm presents stable prediction performance. Verified by parameter prediction and physical experiments, the overall forming deviation of machined parts is controlled within ± 1.0 mm, which meets the industrial forming requirements. It is demonstrated that the proposed prediction method can realize rapid and high-precision forming of integral panels during the shot peening process.

In future research, the full process chain covering milling, shot peening and surface strengthening involved in integral panel manufacturing will be integrated into the shot peening path planning system. A novel process parameter calculation method will be established by considering the deformation induced by previous processes and the strengthening effect of subsequent processes, so as to further enhance the prediction accuracy of process parameters for integral panel shot peening.

7. References

- [1] A. A. Zhao, X. J. Zhang, G. Q. Gao, L. B. Liu, and Y. J. Wang, "A systematic method of shot peen forming of large integral wing skin panels," *Acta Aeronautica et Astronautica Sinica*, vol. 40, no. 2, pp. 522635, 2019.
- [2] V. Sushitskii, P. O. Dubois, H. Y. Miao, M. Lévesque, and F. Gosselin, "Simulation and automation of aluminum panel shot peen forming," *International Journal of Material Forming*, vol. 17, no. 3, p. 25, 2024.
- [3] V. Nguyen, T. Ba, A. Teo, K. Ahluwalia, A. Aramcharoen, and C. Kang, "An internal model-based PID control for smart shot peening operation," *Digital Manufacturing Technology*, pp. 15 – 33, 2021.
- [4] D. L. Baughman, "Method and apparatus for imparting a simple contour to a workpiece," U.S. Patent 4 694 672, Sep. 22, 1987.
- [5] X. D. Xiao, "Modeling of shot peening stress field and simulation of strip shot peen forming of integral deformation" (in Chinese), Ph.D. dissertation, Northwestern Polytechnical University, Xi'an, China, 2015.
- [6] R. Qin, Z. F. Zhang, J. M. Griffin, J. Huang, G. R. Wen, W. F. He, and X. F. Che, "Incorporating

machine learning in shot peening and laser peening: A review and beyond," *Advanced Engineering Informatics*, vol. 65, p. 103350, 2025.

[7] C. Liu, Z. Y. Zhao, X. J. Zhang, and J. B. Wang, "A progressive approach to predict shot peening process parameters for forming integral panel of Al7050-T7451," *Chinese Journal of Aeronautics*, vol. 34, pp. 617-627, 2021.

[8] T. Wang, J. B. Wang, X. J. Zhang, and C. Liu, "A Study on Prediction of Process Parameters of Shot Peen Forming Using Artificial Neural Network Optimized by Genetic Algorithm," *Arabian Journal for Science and Engineering*, vol. 46, pp. 7349-7361, 2021.

[9] X. J. Zhang, T. Wang, J. B. Wang, and C. Liu, "Analytical modeling of shot peen forming process using cross-sectional linear indentation coverage method," *International Journal of Mechanical Sciences*, vol. 133, pp. 838-845, 2017.

[10] H. Y. Miao, et al., "An analytical approach to relate shot peening parameters to Almen intensity," *Surface and Coatings Technology*, vol. 205, no. 7, pp. 2055-2066, 2010.

[11] J. S. Chen, et al., "Literature review of numerical simulation and optimisation of the shot peening process," *Advances in Mechanical Engineering*, vol. 11, no. 3, p. 1687814018818277, 2019.

[12] D. Y. Hu, Y. Gao, F. C. Meng, J. Song, Y. F. Wang, M. X. Ren, and R. Q. Wang, "A unifying approach in simulating the shot peening process using a 3D random representative volume finite element model," *Chinese Journal of Aeronautics*, vol. 30, no. 4, pp. 1592-1602, 2017.

[13] X. Xiao, S. Chen, J. Du, Y. Zhang, Z. Tan, and Y. Li, "Graphically planning of strip peen forming parameters with generative adversarial networks," *Journal of Manufacturing Processes*, vol. 150, pp. 432 – 444, 2025.

[14] C. Li, A. Amanov, Y. Li, C. Wang, D. Wang, and M. A. Wahab, "Prediction of residual stress distribution induced by ultrasonic nanocrystalline surface modification using machine learning," *Advances in Engineering Software*, vol. 188, p. 103570, 2024.

[15] B. Li, Z. Qin, H. Q. Xue, Z. D. Sun, and T. Gao, "Optimization of shot peening parameters for AA7B50-T7751 using response surface methodology," *Simulation Modelling Practice and Theory*, vol. 115, p. 102426, 2022.

[16] X. L. Wang, Z. Wang, G. Wu, J. Gan, Y. Yang, H. M. Huang, J. X. He, and H. L. Zhong, "Combining the finite element method and response surface methodology for optimization of shot peening parameters," *International Journal of Fatigue*, vol. 129, p. 105231, 2019.

[17] Y. S. Nam, U. Jeon, and H. K. Yoon, "Use of response surface methodology for shot peening process," *International Journal of Advanced Manufacturing Technology*, vol. 87, pp. 2967 – 2981, 2016.

[18] C. A. Wang and T. Kim, "Optimization of parameters for the best shot peening effect based on surface response and neural network model," *Materials Research Express*, vol. 11, no. 1, p. 016509, 2024.

[19] O. Unal, "Optimization of shot peening parameters by response surface methodology," *Surface and Coatings Technology*, vol. 305, pp. 99-109, 2016.

[20] Z. Y. Wang, et al., "Process-based deep learning model: 3D prediction method for shot peen forming of an aircraft panel," *Chinese Journal of Aeronautics*, vol. 36, no. 11, pp. 500-514, 2023.

[21] J. Q. Shang, S. Tian, P. T. Gai, F. L. Chen, and Y. S. Zeng, "Stretch-bending prestressed shot peen forming technology and its application for integral panels with stiffeners" (in Chinese), *Journal of Mechanical Engineering*, vol. 60, no. 14, pp. 97-108, 2024.

Foundation items: Project supported by the National Natural Science Foundation of China under Grant No. 52575446。