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Precise Shoe-Material Cutting Using Image-Based Die Cutter Calibration for Punching Machine Tools

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In this paper, a set of stable auxiliary positioning modules for die-cutting shoe material by means of image-based die-cut calibration is proposed. Used in combination with a self-developed polygonal-object packing system for shoe-material cutting, the punching machine tool can automatically cut accurately, stably, and efficiently with the highly integrated hardware and software. In particular, the packing of the shoe material is based on the contour of the die-cut mold vector, and the object-dilation method is used to maintain a fixed gap between the objects. Then, a search method is employed to calculate a compact packing of the die-cut contours. The center point and azimuth angle of the die-cut contours are determined through object packing by a heuristic search. The contours of this die-cut are projected directly onto the positioning module. The physical die-cut mold is aligned with the images, and then the die-bar is locked to complete the die positioning, which is synchronized with the packing system. This new die-cut calibration method is more accurate and reliable. Moreover, the error in the gap between the material and the die-cut was ±0.1 mm, which is in line with the development trend of automatic precision die-cutting.

Keywords: Die Cutter Calibration, Object Packing, Punching Machine Tools, Shoe Material Cutting

1 Introduction

The full automation of machine tools is anticipated to be a key driver in the advancement of Industry 4.0 [1–5]. In particular, the automation of machine tools is gaining increasing attention from industry professionals, as it enhances equipment flexibility while enabling fast and efficient processing.

The accelerated integration of conventional management systems, manufacturing processes, and machine tools from the past is greatly expected, and a higher degree of automation should also be achieved in the process. This requires a machine tool to not only be intelligent and automated, but also flexible in operation.

Taking the "mother of machine tools," i.e., the computer numerical control (CNC) machine, as an example, many functions have been developed to meet the above requirements, such as director numerical control (DNC), auto tool change (ATC), and the application of computer-aided manufacturing software (CAD/CAM). These functions have solved many problems in machining precision, efficiency, and required manpower. The development of new functions for machine tools has always been urgently needed, especially those used for machining processes. The tool calibration and compensation are closely related to the precision of the machined workpiece.

In the application of various types of machine tools, laser optical measurements or machine vision systems are often adopted in the calibration process of cutting dies and/or milling tools. For example, in 2020, Xu et al. [6] proposed a non-contact laser imaging system that allows on-line measurement of CNC tools without the need to remove the workpiece. By modifying the numerical control (NC) program to compensate for tool-setting errors, this approach achieves nanometer-level precision in multi-axis machining. Fang et al. [7] presents a novel calibration method for laser tool setters, crucial for precise tool measurement in smart manufacturing. The study develops a precise mathematical model using polygon clipping algorithms to determine compensation distances for accurate calibration. A kinematic chain-based method is introduced to correct laser beam misalignment. By simulation and experimental validation confirm the method's effectiveness, improving calibration accuracy and enhancing CNC tool measurement precision. Different from optical measurements and calibration systems, Hou et al. [8] have applied machine vision and image processing techniques to establish a mapping relationship between images and machine tool coordinates based on feedback from CNC machine tool position information. The growing applications of vision-based methods lead to user-friendly visualization of tool settings and automatic online tool calibration to enhance the machining accuracy of machine tools.

Regarding the development of probes for tool calibration, Ibaraki et al. [9] introduced an R-test probing system to calibrate the motion errors of the rotary axes in five-axis machining centers. The proposed algorithm automatically identifies location errors and position-dependent geometric errors. Building on this work, a new contact-trigger probe presented in [10] is mounted to the machine spindle to calibrate rotary axis positioning errors in five-axis machining centers through on-the-machine measurement of a test piece.

Recently, Liu et al. [11] reviewed various tool alignment methods and classified them into contact and non-contact types. While tool measurement, calibration, and compensation for CNC machine tools have seen significant advancements, there is, to the best of our knowledge, no prior research focused on precise cutting for punching machines. Therefore, the development of non-contact, vision-based calibration procedures for traditional, widely-used punching machines would reduce material waste and improve production efficiency, particularly in applications such as shoe manufacturing.

At present, punching machine calibration uses two sets of simple parallel mechanisms to obtain the smallest bounding box of the die and then lock it, as shown in Figure 1. However, the dies usually have different geometric contours. Therefore, despite this simple packing system, which helps arrange the batches of dies, it is often only possible to arrange and lock the dies while also relying on visual inspection, experience, or trial and error, in the absence of a reliable calibration system and with an unclear understanding of the inter-relationships of the manufacturing processes. When the center point and azimuth angle of the die contour cannot be defined, based on the packing system, the problem of the interference and gap asymmetry will inevitably arise during the actual die-cut, as shown in Figure 2. The current solution is to repeatedly fine-tune the position of the die cutter and increase the packing gap of the shoe material by trial and error. This increases the time and material consumption of the punching process, and easily causes the risk of faulty operation. As a result, although most current punching machines are equipped with simple packing systems, they still cannot improve the precision and compactness of the punching process.

Therefore, this study systematically analyzes the correlation between the die and the punching machines process. Through the integration of software and hardware, a dedicated die-cutting system is proposed, in the hope of improving the accuracy of the shoe-material die-cutting process.

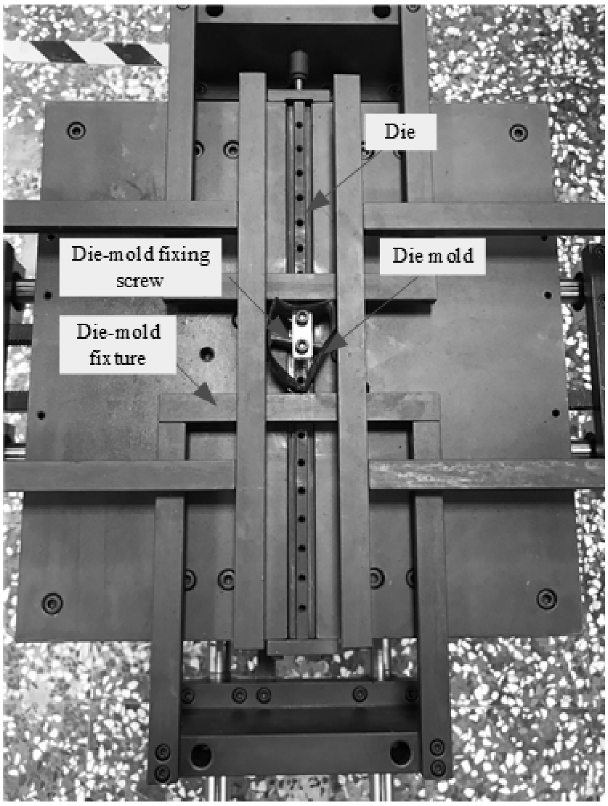


Fig. 1 *Conventional die positioner*

Fig. 2 *Overlap and asymmetric gaps*

2 Experimental Apparatus and Method

This study will investigate the precision of punching machine tools commonly used in the industrial processing of shoe materials. The experimental apparatus is a hydraulic four-axis die-cutting machine tool (X,Y,Z,C), as shown in Figure 3.

The machine tool is mainly composed of a displacement platform and a die-cutting head. The movement of the die-cut (X), the rotation of the tool holder (C), and the displacement of the platform (Y) are controlled by a lead screw driven by a 1-kW servo motor. The die-cutting action is achieved using a hydraulic cylinder to drive the linkage mechanism, which makes the die-cut produce reciprocating die-cuts (40 tons), while maintaining the parallelism between strokes.

The control software and human–machine interface are written in C#. The interface is equipped fully with process control functions, including a start-up-mechanism safety inspection, die-cut sequence, co-position cutting, cutting origin setting, cutting quantity system, unit cutting time control (based on material characteristics), and so forth. It also integrates with the self-developed shoe-material packing system, allowing the display of the packing and cutting progress to be on the human–machine interface, as shown in Figure 4.

To automate the punching machine tools, it is necessary to create a highly compact packing, according to the die contour, before manufacturing. The software for the die-mold contour packing is developed, based on the vector-object field-extension algorithm. In particular, the calculation of the vector-object field extension is achieved by translating each side of the polygonal object by a distance d in the normal direction and taking the intersection point of each two sides as the vertices of the extended edges of the object, as shown in Figure 5.

After the correct object extended edges are obtained, an object-alignment algorithm is introduced to allow the two polygonal objects in the two-dimensional space to be searched and calculated with different rotation directions to group the objects into a compact packing. The current packing system can provide nearly 100 combinations. The user can select the appropriate shoe-material die-cutting packing mode, obtain the optimal packing combination, according to the layout range and the geometric shape of the die, and assign the die contour a new rotation center and azimuth angle, as shown in Figure 6.

Prior to the punching process, it is necessary to lock the die mold onto the die-bar fixture, and then insert the die-bar fixture into the die holder. Because the die holder is equipped with a positioning jig, the center point of the inserted die fixture will coincide with the center point of the die holder. This is when the relevant mechanical parameters, according to the punching process and the material characteristics, can be set through the human–machine interface, and then a series of automatic punching processes can be carried out.

However, because a conventional die-calibration module is not integrated with the packing system, the die cutter is often positioned at an offset, which leads to the problems of undercuts, overlap and excessive die-cut gaps. This is different from conventional die-mold positioning, as it must rely on trial and error, based on experience, or simple jigs.

In this study, a set of equipment that can directly project the contour, rotation center, and azimuth angle of the die cutter onto the die-bar fixture is developed in combination with the packing system. The user only needs to place and lock the physical die cutter, based on the contour image of the die, to accurately complete the calibration procedure.

The new die-mold calibration auxiliary system is composed of two micro projectors (with a projection ratio of 1.55:1), which are capable of accurately projecting onto the fixture, according to the center and azimuth angle of the die-mold contour defined by the packing system, as shown in Figure 7. To ensure the accuracy of the coordinates of the die image projected onto the locking plane, the projection system needs to undergo homography calibration, as shown in Figure 8.

It is necessary to convert the non-orthogonal image of the projector (possibly skewed) into a square 2D plane coordinate on the plane of the solid fixture. This coordinate-system conversion can be achieved through the calculation of a homography transformation. Assuming that a coordinate point X_i (unit: pixel) on projection-image plane 1 corresponds to the coordinate point X_i' (unit: mm) of physical-fixture plane 2, a projection-conversion matrix H exists between the two planes to carry out the coordinate conversion by $\mathrm{X}_i' = \mathrm{H}\mathrm{X}_i$.

In the development of the projection-calibration system, it is possible to use the projection of a checkerboard image and the measurement of the grid points on the fixture's plane to calibrate the projected image and the physical-projection fixture plane to obtain the conversion matrix H.

The dual projection is used to compensate for an image occluded by the die. The intersection of the yellow lines is the center point of the die image, and the red lines are the contour and orientation of the die. The user can follow the contour of the die image to insert and lock the physical die to complete the die cutter positioning.

Fig. 3 *Industrial punching machine tool*

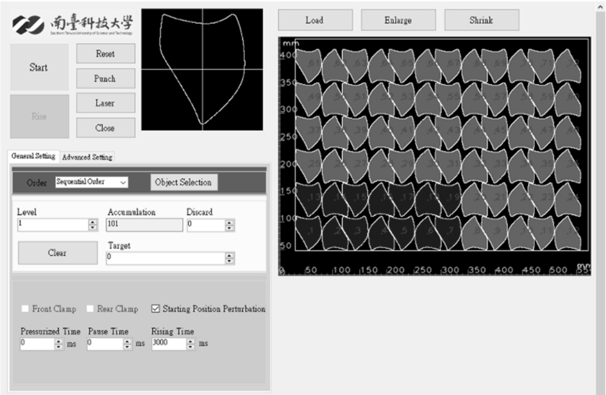


Fig. 4 Human–machine interface of an integrated packing system

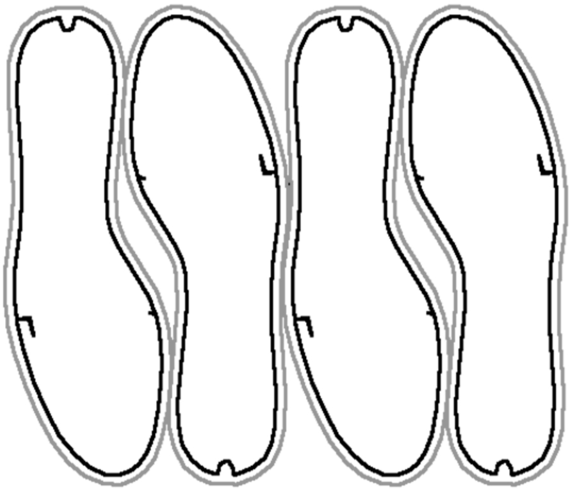


Fig. 5 Vector-extension results of the sides

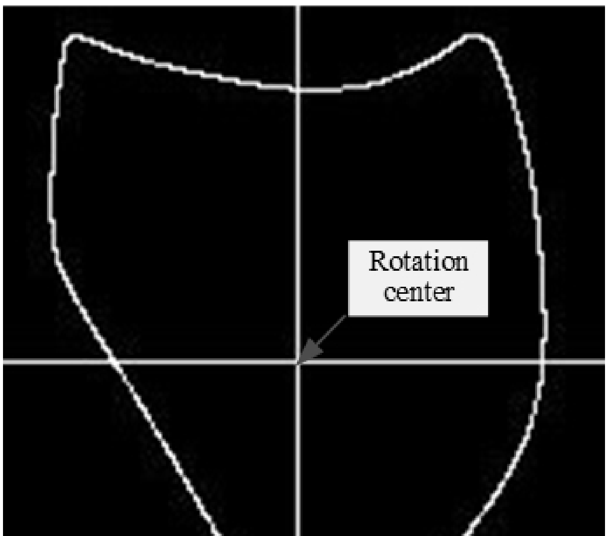


Fig. 6 Schematic of the center point and azimuth angle of a polygonal object calculated by the packing

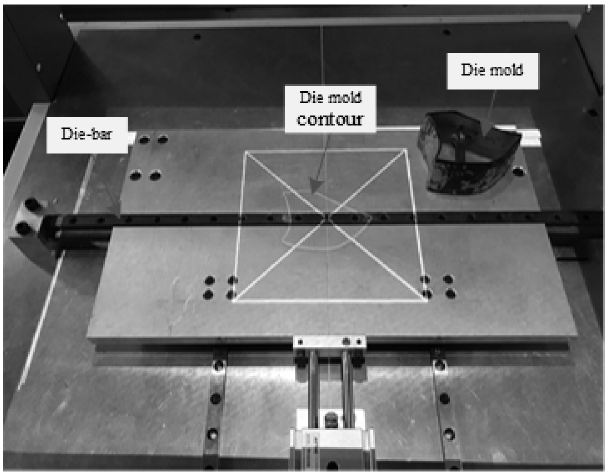
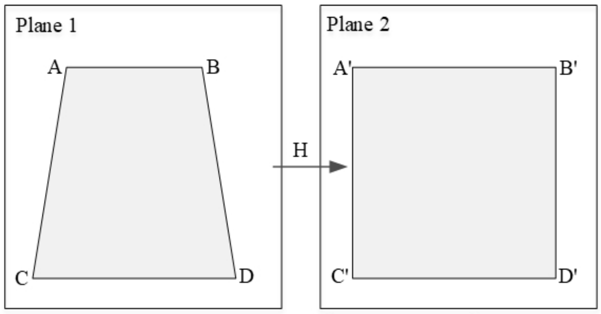


Fig. 7 Schematic of a die-mold contour projected onto a die-bar fixture



$$X' \times HX = 0, \text{ with } H=\begin{bmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{bmatrix}$$

Fig. 8 H: Homography-plane conversion matrix; plane 1: image plane projected by projector; plane 2: target plane calibrated by homography conversion

3 Process Analysis and Result Discussion

The automatic punching process is not complicated, in terms of preparing for the manufacturing process. The contour-image data of the die cutter should be first obtained; the compact packing of the set range is then performed automatically. After the packing results are imported into the machine tool and the reference point for the punching and the machining parameters are selected, the automatic punching process can be carried out. The accuracy of the punching results is affected, not only by the stability of the mechanical structure and control system, but also by the die cutter being accurately positioned more easily. The die cutter needs to be positioned accurately and locked onto the die bar, which is then inserted into the die holder of the machine tool.

During an automatic punching, the physical die cutter can be driven by the die holder to rotate to the angle set by the shoe-material packing system. Together with the displacement of the die holder (X) and the platform (Y), the center of the die cutter can accurately move to the coordinate for die-cut processing.

Consequently, the packing system, die cutter, die bar, and die holder are interdependent. As shown in Figure 9, if the center point and azimuth angle of the physical die cannot be accurately positioned with the die bar, the die embedded in the die holder will have complex interactions during displacement and rotation, such that even the most sophisticated packing system and machine tool cannot present compact punching results.

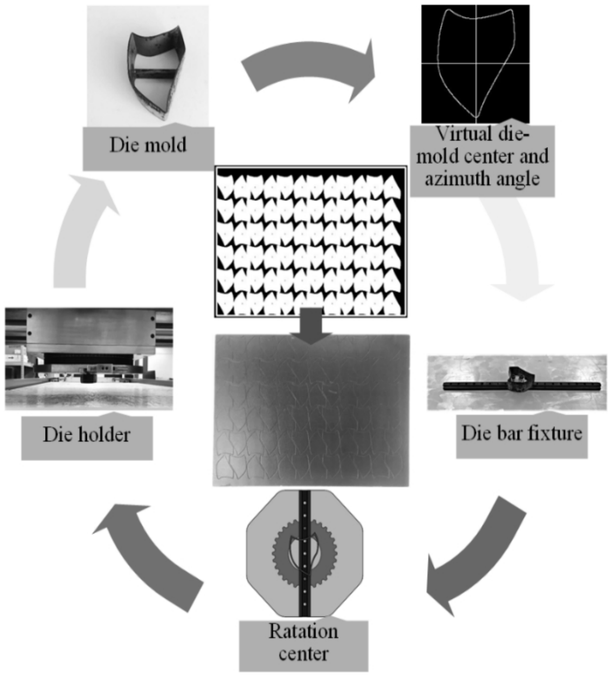


Fig. 9 *Interdependence between the die-mold contour, physical die cutter, die bar, and die holder*

The die cutter geometry is diverse and complex, owing to the requirements of the manufacturing process. Because it is even more difficult to obtain the rotation center point and azimuth angle of the physical die with the shoe material from the packing system with a simple jig, the combination of the physical die cutter and the die bar often have offset problems.

The incorrect offset situations can be roughly divided into three types: X-axis offset, Y-axis offset, and azimuth-angle offset, as shown in Figure 10. The synchronized packing of the heart-shaped die in a fixed range (245 × 240 mm²) is taken as an example. If adjacent die cutters are placed with a 2 mm gap in between, 20 die cutters can be placed in the packing, as shown in Figure 11(a). However, if the die cutter has the correct azimuth angle but X-axis and Y-axis offsets for its center point, the die-cut will be undercut for an entire row or column, causing a loss of at least four to five pieces of finished products, as shown in Figures 11(b) and (c). If the die cutter is concentric with the center of the die bar but with an offset in the azimuth angle, an entire column will be undercut during the actual die-cut, and five pieces of finished products will be lost, as shown in Figure 11(d).

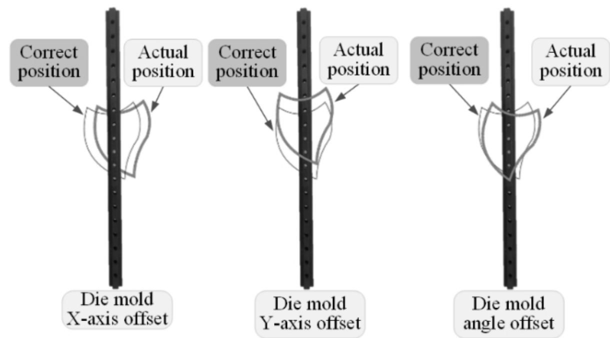


Fig. 10 *Positioning errors between die cutter and die*

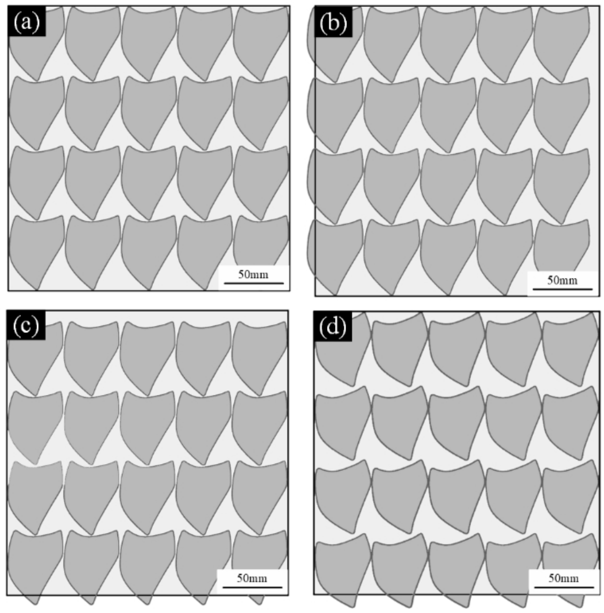


Fig. 11 *Simulation of possible problems caused by die cutter offsets to the die-cut: (a) die cutter center point and azimuth angle aligned with packing system; (b) with X-axis offset; (c) with Y-axis offset; (d) die cutter center point is aligned but azimuth angle is offset by 3°*

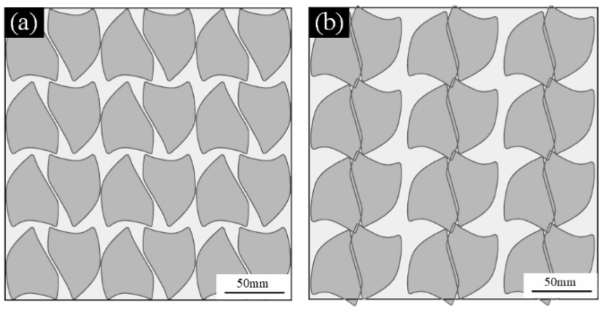


Fig. 12 *Compact packing when (a) die cutter center and azimuth angle are aligned; (b) with X-axis offset and azimuth angle offset*

It is worth noting that, without a special request for the pattern direction of the shoe material to cut, different combinations of die-and-mold directions often appear in the packing (in the range of 264 × 252 mm²) to achieve the highest packing density given the range, as shown in Figure 12(a). Therefore, if the physical die is locked with X-axis and Y-axis offsets as well as an azimuth angle offset, it will cause all the die-cut slices to overlap each other, as shown in Figure 12(b), and the loss rate will reach 100%.

It can be seen from the analysis above that if the physical die cannot be accurately positioned, according to the die center and azimuth angle set by the packing system, before die-cutting, defective parts will be unavoidably manufactured. Increasing the packing gap and adjusting the position of the die by trial and error is the current method of resolving the overlap problem.

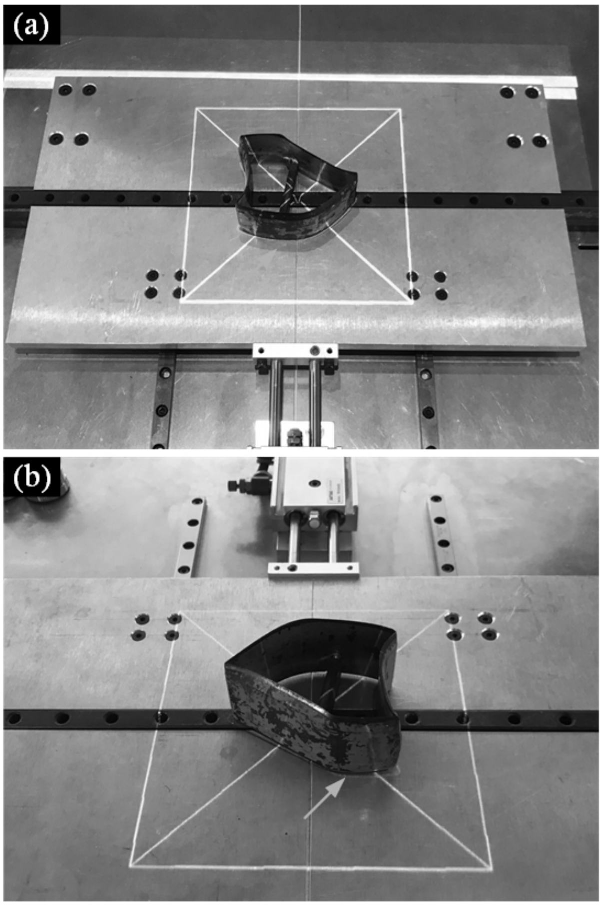


Fig. 13 Red line at the arrow is the projected die contour: (a) front view; (b) rear view

The interactive image-based die-calibration module developed by this research institute can align the contours of the die cutter (including the center point and azimuth angle) obtained by the shoe-material packing system. The dimensions of the physical die cutter are projected directly onto the die-bar fixture, and the contour of the die cutter coincides with the two center points of the die bar (which are concentric). Thus, the user only needs to align the physical die with the projected die profile to complete the die calibration. As shown in Figure 13, the die can be locked into the die holder (C axis) of the punching machine tool. Through the axis-control system with the movement of the coordinates and azimuth angle of the die in the packing, a precise die-cut can be carried out automatically.

The heart-shaped die cutter is taken as an example to conduct a practical experiment. The packing has a 2-mm gap (in a range of 270 × 340 mm^2), which is shown in Figure 14(a). Paper is used as the material (t = 0.14 mm) for the actual die-cut, as shown in Figure 14(b). As can be seen from the figure, the die-cut result is exactly the same as the packing orientation, and the gap between each die is actually between 1.9 and 2.1 mm from measurements. Figure 15 shows that the die-cut result shows no overlap for the entire layout. It is obvious that the packing system, combined with the image-based die contour projection technology, can provide accurate and reliable alignment assistance for the physical die.

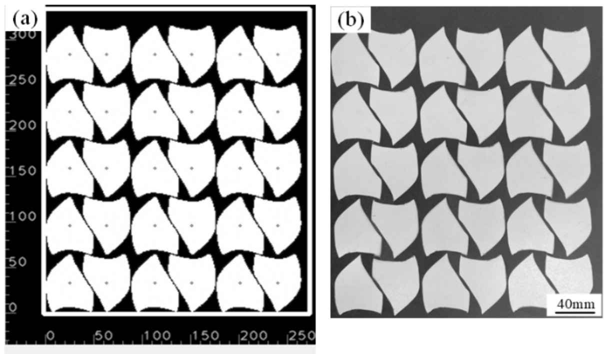


Fig. 14 (a) packing; (b) actual die-cut result

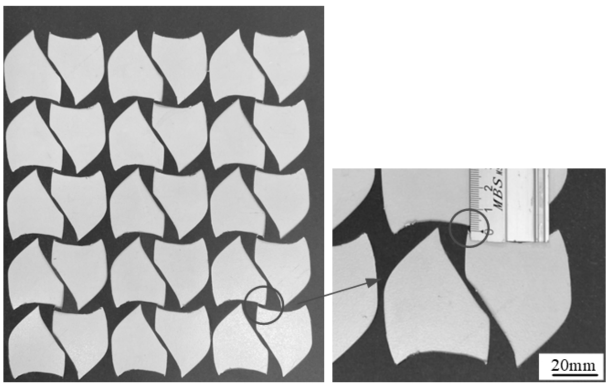


Fig. 15 Minimum gap between die cutters measured at approximately 2 mm

4 Conclusion

This paper discussed the machining accuracy of punching machine tools and proposed a set of innovative technologies for improvement. After an in-depth analysis, a high degree of interdependence was found among the packing system, die cutter, die bar, and die holder. The center point and azimuth angle of the defined die contour will change, according to the different selected packing styles (compactness); hence, the positioning of the physical die needs to be changed according to the packing system definition.

To provide stable and accurate positioning of the physical die, an image-based die-calibration module that can be combined with the packing system was developed. The module projected the contour, center point, and azimuth angle of the die-mold image directly onto the die-bar fixture at a ratio of 1:1. With this intuitive and visual operating environment, the physical die cutter was assisted to align with the projected die contour, and the positioning of the physical die cutter was completed concisely, based on the integration of a virtual image and reality.

The die-mold gap after an actual die-cut could be controlled within 2 mm, according to measurements, which proves that the image-based die calibration can not only improve the die-cut accuracy, but also greatly shorten the calibration time. Moreover, owing to the modular design of the image-based die-calibration method, only one calibration module can satisfy the calibration needs of countless sets of punching machine tools and physical dies, which is quite cost effective.

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