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Original research article

Application of Quality Function Deployment (QFD) in Die Redesign to Lowering Rework of Stamping Parts

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ABSTRACT

In this work, QFD was utilized in die redesign to solve burrs and incorrect dimension defects in the stamping part. Because of these defects, almost 87% of processed parts were reworked in one industrial case. Based on root cause analysis, the burrs and incorrect dimension defects resulted in the cam piercing, piercing, and separating on compound dies of the existing stamping process. Dies configuration is indicated as the cause of these defects. This study aims to decrease the defects. The work consists of problem identification, RCA, die planning using the House of Quality of QFD phase 1, die design using QFD phase 2, and fabrication and assembly using QFD phase 3. Finally, QFD phase 4 tests the design die with 1,000 tons load and 30 samples in regular production and then analyzes. The result shows that reworked parts decreased from 87% to 0%. It concluded that QFD can be applied effectively in this work.

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1. Introduction

Die stamping is a manufacturing process that is commonly used for sheet metal. A press machine produces stamping parts from sheet metal as raw material [1]. This process uses only one machine type and dies set. Die is the only tool used for cutting and forming sheet metal to form a product. The product's accuracy, shape, and size depend on the die's quality [1], [2]. The die type can be simple, progressive, or compound, depending on the type of machine, capacity, and material to be processed. This stamping process is commonly used in mass production to fabricate many sheet metal products, such as automotive and other construction parts.

Dies are assembled on a frame of a press machine to process several intended works on sheet metal, such as forming (bending, deep drawing, embossing) and cutting (blanking, piercing, cutting). The die tooling consists of several main components: punch, dies, punch holder, die holder, springs, and guides. Stamping product quality is strongly influenced by one or a combination of three factors: material, dies (tooling), and stamping machine. In this work, material and a press are standard; therefore, it focuses on tooling. Tooling includes dies configuration that

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forms and cuts the raw material in sheet metal form. Dies become a significant part of the stamping process; the optimal performance of dies depends on their design and construction. This field investigation found burr and incorrect dimension defects in the stamping part. Burr is a sharp portion on the edge of the part. Based on Root Cause Analysis (RCA), the burr and incorrect dimension defects were created from compound dies' piercing, cam-piercing, and separating processes. This configuration failure was due to the failure of the locator of the piercing cam, piercing, and separating caused by previous incorrect corrective actions. Therefore, the die configuration should be changed because, besides the burr, the dimension part produced also did not face the standard. The Quality Function Deployment (QFD) method is used in the design process of the die to diminish these defects.

QFD is used to optimize the die design in this work. QFD translates users' needs to produce a more specific product or process qualification [3]–[5]. It correlates the customer's requirements and the designer's innovative ideas, usually made in a matrix. This research uses QFD Phase 1 product planning (Matrix I), QFD Phase 2 die design (Matrix II), QFD Phase 3 fabrication and assembly (Matrix III), and QFD Phase 4 control product (Matrix IV). All Phases of the QFD matrix used the House of Quality (HOQ) tool. By HOQ Matrix, the design was made based on consumer demand with several alternative design concepts based on the problem of making the stamping part (Phase 1), calculating each part's engineering aspect (Phase 2), manufacturing (Phase 3), and controlling the products (Phase 4). This work aims to design dies to produce high-quality stamping parts without burr defects and fulfill the standard. Therefore, rework does not need to correct the products.

2. State of the Art

2.1 Quality Function Deployment

QFD is a method of improving quality by focusing on customer needs [6]–[8]. A high-quality product fulfills customer needs and satisfaction. Then, Quality improvement can be pursued through all phases of design and process: product planning, product design, process planning, and process control planning, as elements of the QFD matrix, as shown in Figure 1. In product planning, as Phase 1 of QFD (Matrix I), customer requirements are translated into design requirements (specifications), benchmarks for the competitors, and developing and selecting the appropriate concepts. Product design as Phase 2 of QFD (Matrix II) includes identifying critical parts and their characteristics, final product specification, and product risk identification. Process Planning as Phase 3 QFD (Matrix III) defines process planning based on matrix II output's critical component parameter. This process involves planning the manufacturing process and identifying critical process control. The last stages of QFD (Matrix IV) include defining the process for each component and determining quality indicators, measurements, and inspection methods.

HOQ is a critical component of the QFD technique. It specifies the correlation between customer needs, satisfaction, and product requirements. HOQ is involved in QFD mainly in collecting and analyzing the voice of customers (Matrix I of QFD). HOQ example is shown in Figure 2 below. It starts with customer needs identification, engineering needs, connecting customer and technical needs, conducting competitive analysis, and technical desires [10], [11]. Thus, HOQ is very important in product design development and the following stages in implementing QFD to realize the product.

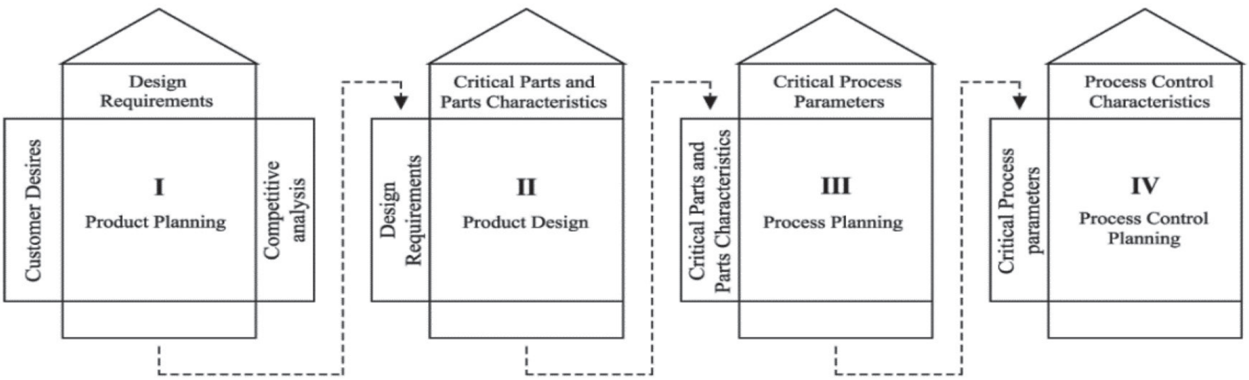

Figure 1. The phase of the QFD process [9]

Based on Figure 2, part A lays out the customer's needs. Customer needs identification is collected from the customer environment. Part B is a planning matrix based on market competition of similar products or services. Part C is a technical measure that assesses each customer's needs. Which one is the most important of those customers' needs? Part D is the interest between the matrix of customer and technical needs. Part E is the correlation matrix, and Part F is the technical matrix. This HOQ matrix, part of QFD, will be used in the die redesign to decrease or eliminate burr defects in the fabrication of stamping parts. HOQ matrices are also used in all stages of QFD.

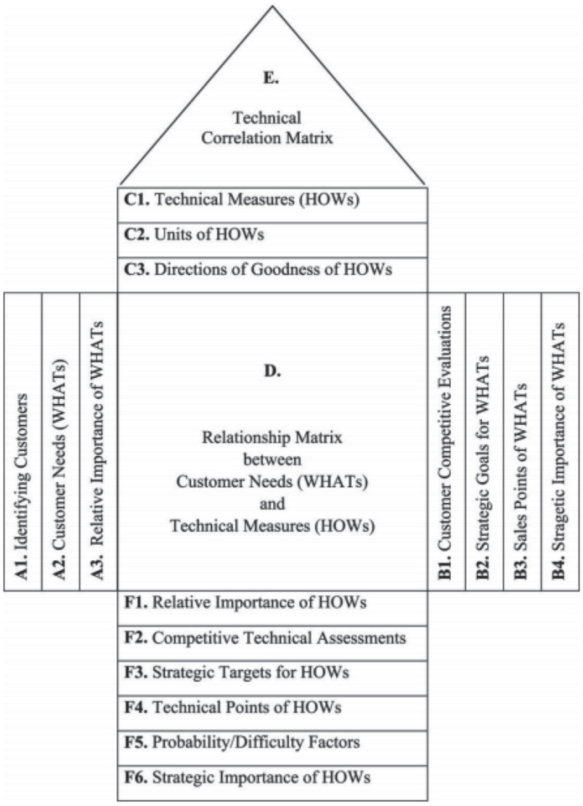

Figure 2. House of Quality (HOQ) [4]

2.2 Related Works

Some studies on QFD have been implemented in many engineering fields. Bond et al. [6] used the QFD matrix in selecting metal-forming processes. In this work, a QFD process analyzes the selection of a combination of a material and its unification process. The correlation and selection matrix chooses the best design that suits their needs. Kasaei et al. [7] used the HOQ method of QFD in the material selection process. HOQ is implemented in providing a charge on every option available in material selection. Rianmora and Werawatganon [8] also used QFD in the design process of a water-filling machine. This work used the Kano model and QFD analysis to make the machine more effortless for the public. This research began by spreading questionnaires to smaller groups. Thus, the data can be analyzed and adjusted to the community's needs as its users. Siswiyanti et al. [9] researched the process of making batik dyeing machines, where the machines were analyzed for their negativity. The degree of the economy is compared to the output level of the number of batiks successfully colored.

Shen et al. [14] developed a digital platform using the QFD method. The QFD evaluation was conducted using an online questionnaire-based customer voice. The customer-oriented design is used to analyze the needs of the digital platform design priority. Another fuzzy method called multi-criteria group decision is used in developing digital platforms using QFD [13]. Yang et al. [15] also developed a new QFD method based on the large-scale-group decision. This method was applied in developing photovoltaic solar cells. The analysis was also made to compare the proposed QFD method with the traditional QFD method. QFD was also applied to the apartment building development [16] and the future airport [17]. Another case study on using QFD in research is the fuzzy method applied in developing electric vehicles [18]. The advantages of using QFD are that it improves anchoring orientation, product effectiveness, and communication and cooperation [12], [19]. Some studies above show that QFD has been quite reliable in using product development.

3. Materials and Methods

3.1 Stamping Part and Material

The stamping or press part is fabricated using compound dies in this research. Several forming and cutting processes are implemented in compound dies in one stroke. These stamped parts are produced pairwise, called RH-part (right side) and LH-part (Left side), and fabricated in one stroke using compound dies that are designed in this work. The parts are truck-type vehicle components. This part will be assembled to reinforce the truck's frame structure. The geometry of the press part is shown in Figure 3.

The stamping part is made of SAPH 440 steel plate. Automotive manufacturers commonly use this steel plate as a vehicle structure material. It is commonly utilized as reinforcing structures in heavy vehicle frames. The thickness of the SAPH 440 steel plate is 4.5 mm. This steel plate's chemical composition and mechanical characteristics are shown in Table 1 and Table 2 below, respectively.

Figure 3. Press tamping part LH (left side)

Table 1. Chemical composition of SAPH 440

Classification symbol	Chemical Compositions	
	P (%)	S (%)
SAPH 440	0.040 or below	0.040 or below

Table 2. Mechanical Properties of SAPH 440

Classification Symbol	Tensile Strength (MPa)	Yield point (MPa)	Elongation (%)
		Thickness ≤ 6.0 mm	Thickness, 4.0 - 6.3 mm
SAPH 440	440	305	34

Burrs and incorrect dimensions became the main problem in this case study. They are found on the right and left side of the cutting side part cut by cam-piercing, on the top of plate metal products cut by piercing, and on separating parts (LH-part and RH-part) in the form of sharpening produced by separating cut. At the same time, incorrect dimensions are caused by the shift of punches after corrected maintenance. Thus, the defects affect part quality. Burr can occur due to several factors, including the cut side of the punch or an already blunt die. The other factor is that the clearance between the punch and dies needs to be close enough according to the standard. It can cause a burr around the perimeter of the product or in certain parts of it.

In this case study, the press parts were fabricated using the existing dies that have several repairs, producing excess burrs and incorrect dimensions (shifted). These excessive burrs and incorrect dimensions are a hardship because the press part will be assembled or placed with other components. If the press part produces many burrs and incorrect dimensions, then the press part cannot be used and will be rejected or reworked, which causes losses to the manufacturer. The location of the burrs is illustrated in Figure 4 below.

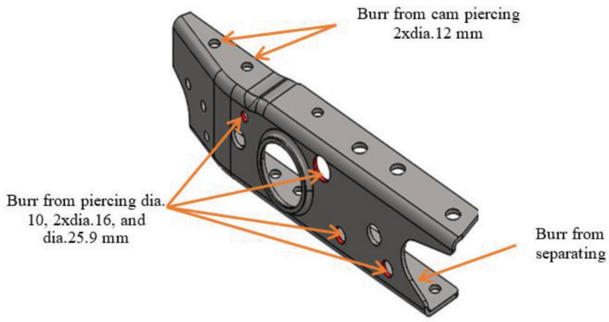

Figure 4. The location of the burrs in the LH-press part

3.2 Methods

The stages of work carried out for the redesign process die, including piercing, separating, and cam-piercing, are as follows. Firstly, problem identification. Secondly, root causes analysis (RCA) of the die defect. Dies planning and design use the QFD phase 1 and phase 2, respectively, as step three. Fourthly, part fabrication and assembly as the implementation of QFD Phase 3. Finally, test and analysis the die as QFD Phase 4.

In problem identification, burrs, and incorrect dimensions were produced in part fabrication using existing dies. Burr is one of the defects where a sharp edge of the part results from the pressing process. Detail burr is shown in Figure 5. Some critical parts' dimensions were out of specified standards (incorrect dimensions). Therefore, more than 87% of the parts had to be reworked.

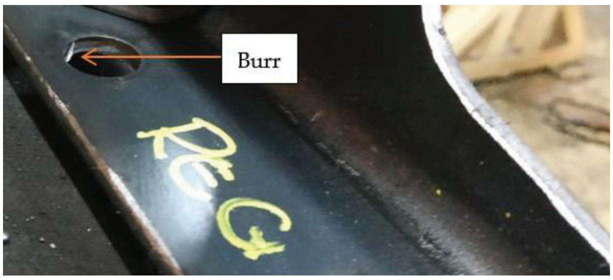

Figure 5. Detail of Burr on a Press Part

A comprehensive root cause analysis is carried out from the beginning to the end to identify the occurrence of the defects. Analysis and checking include plate material and thickness, the capacity of the press machine, and the material and dimensions of the dies and punches and process condition. The capacity of the press machine used is 1,000 tons. The press parts material is SAPH 440 steel. While the punch and dies material is SKD11 steel. The material and dimensions of the sheet, punch and dies, and process meet the specifications.

The main problem of part defects was burrs and out of standard in some critical dimensions (incorrect dimensions). Based on the root cause analysis, burs were mainly caused by poor die configurations, such as improper clearance and die and punch wear. At the same time, improper dimensions of the part were mainly caused by the alignment error of the punch and die. The existing die system had permanently attached the locator to the casting base. The existing die configuration is shown in Figure 6. This alignment error is because of the failure of the previous maintenance work on the cam locator. This permanent locator caused complicated maintenance and corrective die process. In addition, the previous corrective action needed to be corrected on the button dies. Poor corrective action had small shifted the button position from its actual position and made it challenging to repair. This action created defects because achieving optimal clearance between punch and die takes time. Permanent failure in existing dies was problematic to repair again. The decision is to change the dies by redesigning the new one.

Furthermore, existing dies were also hard to maintain and not ergonomic. The existing die configuration makes it tricky for the operator to pick up the part punched from the dies. Therefore, the LH and RH parts must be pried to release from the dies. Operators suggested improving the easier retrieval of finished parts from dies. Hence, the design should consider ergonomic aspects, easy to maintain, reliable, and inexpensive.

After identifying problems and RCA, the HOQ of QFD Phase 1 design planning of dies is developed as Matrix 1. Identifying customer needs, functional requirements, and targets are outlined in this HOQ matrix. Focus group discussions of the die development team and customers are implemented to score and refine specifications. In this case, the customers are operators, supervisors, heads of the production department, maintenance technicians, quality control, and manufacturing engineers, while the development team consists of die engineers. Several concepts are built based on the specifications and existing dies as a reference on the HOQ matrix. Teams then choose the best concept and continue to Phase 2 of QFD.

The design process of Phase 2 of QFD is implemented by analyzing the selected concepts, including the engineering specifications of the die buttons and punches as critical components and press machines. Punch strength and clearance between punch and dies are essential in burr forming. Therefore, die part calculation includes cutting force and clearance between punch and die and related dimensions. The cutting force in the punch and die press process is the minimum force required for cutting material. The magnitude of the cutting force, P_s, can be calculated using the equation as follows [20]:

$$P_s = L \times t \times s \tag{1}$$

where L is the part cutting plane's circumference, t is the material's thickness, and S is the shear resistance. Generally, shear resistance is worth 80% of tensile strength.

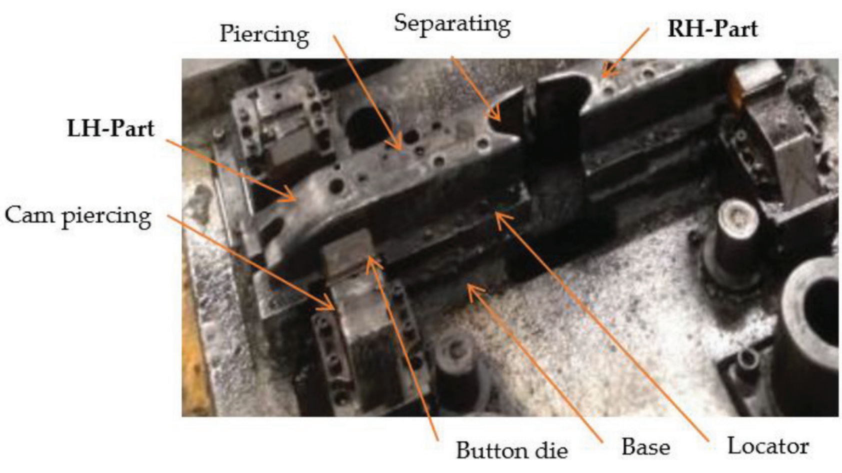

Figure 6. Die Configuration Caused Press Part Defect

Press machine capacity, P_m, can be calculated by using the equation as following [20]:

$$P_m = P_s x S \tag{2}$$

where P_s is the cutting force, and S is the safety factor (typically S = 1.2 -1.5).

The difference between a punch and a die is called an allowance. At the same time, clearance is the gap between punch and dies measured on only one side, in other words, half of the allowance. The clearance value, C, can be calculated using Equations 3 and 4 [20].

$$C = \frac{k \times t \sqrt{0.7 x UTS}}{2} \text{ ,if } t < 3\,mm \tag{3}$$

$$C = \frac{(1.5 \times k \times t - 0.015) \times \sqrt[2]{0.7 x UTS}}{2}, \quad \text{if } t \geq 3 \text{ m} \tag{4}$$

where t is the thickness of the material, UTS is the ultimate tensile strength of the material to be cut, and k is factor correction that value is 0.01.

Punch is one of the essential components of dies. The material of the punch is critical not only because of its hardness and ductility but also its resistance to the workpiece's surface. In addition, the punch's material dimensions must be considered when designing the dies to avoid the occurrence of fractures when carrying out the cutting process. It can be seen in Figure 7 for punch-piercing construction.

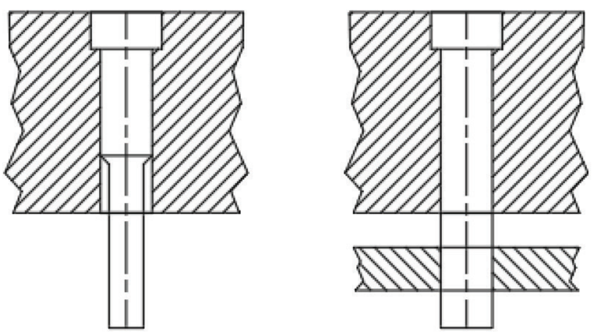

Figure 7. Punch Piercing Construction

The punch length is a critical dimension related to the performance and buckling phenomena. If the punch length is too long, the punch is susceptible to buckling and breaking. To determine the length of the punch piercing [L], the modulus elasticity, E, and moment of inertia should be known. The length of the piercing punch, L, can be calculated by equation 4 [21].

$$L = \sqrt{\frac{\pi^2 \times E \times I_X}{4 \times SF \times (0.7 \times \pi \times D \times t \times UTS)}} \tag{5}$$

where E is the modulus of elasticity, I_x is the moment of inertia, D is the punch diameter, UTS is the ultimate tensile strength of the plate to be cut, t is the thickness of the material to be cut, and SF is the safety factor. The value safety factor, SF, is 2 to 3 for heat-treated steel, and SF is 4 to 5 for non-heat-treated steel.

In addition to the punch, the button die is one of the essential components of dies. It can be seen in Figure 8 (a) for the construction of the button die. The block height (h), according to Oehler's finding in Suchy [21], can be approached by the following equation:

$$h \approx \sqrt[3]{P_m} \tag{6}$$

$$h \geq \sqrt[3]{\frac{(0.7 \times \pi \times D \times t \times UTS)}{g}} \tag{7}$$

where P_{max} is the maximum cutting load, D is the punch diameter (related to hole diameter), t is plate thickness, UTS is the tensile strength of the plate, and g is the gravitation constant (9.81 m/sec^2).

The thickness of the button die is also necessary to know the inner diameter of the button die, which can be seen in Figure 8 for the construction of the button die. In equation 8 below, the diameter of the button die can be determined. If D is the final diameter of the workpiece, δ is the material to be cut, C is the clearance, and d_p is the diameter of the punch, then the diameter of the button die d_m can be calculated as follows [21].

$$d_{\mathrm{m}} = d_{\mathrm{p}} + 2\mathrm{C} = D + \delta + 2C \tag{8}$$

In this case study, the punch material used is SKH51 steel. The diameter tolerance of such punches is ± 0.0005 mm. The button dies used in this study were type MSD A SKD11 with H7 - n5 transition fit tolerance. The punch and button for the piercing and cam-piercing process and separating punch used in this case study are illustrated as shown in Figures 8 (a) and 8 (b), respectively.

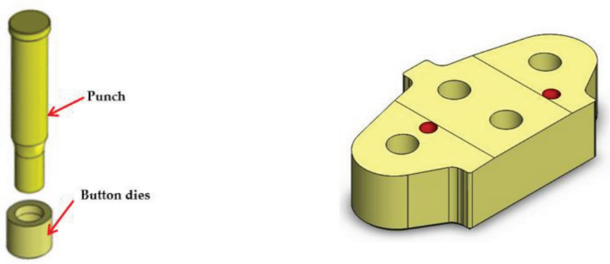

Figure 8. (a) Punch and button die for piercing and cam-piercing, and (b) separating punch

Step 4 is components fabrication and assembly (QFD Phase 3). The process begins with the fabrication of die components and assembly. Finally, Step 5 tests the die to determine whether the tool is running well (QFD Phase 4). The test used 30 pieces, and the test analysis was dimensional for each part in regular production.

4. Results and Discussion

4.1 Dies Press Part

Dies consist of an upper part where the punch is mounted and a lower part where the die is assembled. Pairwise punch and die carry out a particular combination of forming or cutting processes according to the part design. The upper part is mounted on a movable press machine ram, while the lower is mounted on a static bolster. The cutting process occurs when the punch moves downwards to form or cut on the plate, placed on the lower part with several locator pins with a predetermined stroke distance.

Compound dies consist of several single dies and implement several works in sheet or plate metal forming. The critical dies in this work are piercing die, cam-piercing die, and separating die. A 1000-ton AIDA press machine drives compound dies on the extensive press line to perform stamping works. The process consists of blanking (cutting), deep drawing (forming), piercing (cutting), cam-piercing (cutting), and separating (cutting). This research focuses on piercing, cam-piercing, and separating that formed burrs and incorrect dimensions. The formed stamping plate is laid on the surface of the die and guided by a stopper plate.

The stamping or press part is fabricated using compound dies in this work. Several forming and cutting processes are implemented in compound dies in one stroke. These stamped parts are produced pairwise, called RH-part (right side) and LH-part (Left side), and fabricated in one stroke using compound dies. The parts are truck-type vehicle components. This part will be assembled to reinforce the truck's frame structure. The geometry of the press part is shown in Figure 3.

4.2 Quality Function Deployment (QFD)

A complete QFD consists of four HOQ phases: product planning, as shown in Figure 9(a); product design, as shown in Figure 9 (b); process planning, as shown in Figure 9 (c); and process control, as shown in Figure 9 (d). The redesign process begins with the developed HOQ of QFD (Matrix I), as shown in Figure 9 (a). This tool will provide an overview of the customer's needs correlated with the technical specifications. The HOQ product planning shows elements of Matrix I, such as customer requirements, functional requirements and targets, customer importance, and weighted scores. This HOQ (Matrix I) also shows the correlation between customers' needs and the technical specifications of punch and button dies. The team consisting of the die designer, customers (operators, production supervisor, head of production division, and part users), manufacturing, marketing, and finance completed these overall matrices.

Die developing step starts with customer need identification. In this step, customer needs are collected and listed as function, maintenance ability, ergonomics, reliability, and price consideration. The function is the critical requirement for dies and punches. An ergonomic mold system is critical to less maintenance effort and more safety for the operator. In addition, the mold system can also be replaced, assembled, and dismantled quickly in the maintenance process. The productivity of the punch and die is also the most essential need. Another customer requirement is durability, which increased from 80,000 to 100,000 strokes. The last requirement is that the manufacturing cost is affordable. These HOQ matrices of QFD help develop a clear interest in customer needs and provide specific guidance about designing and engineering the die.

The die development team then translates those customers' needs into functional requirements such as dimensions, lifetime, maintenance, productivity, and materials. The team also specifies targets for each functional requirement. The following step of developing HOQ of product planning (Matrix I) is scoring. The development team and customers implement brainstorming in a focus group discussion

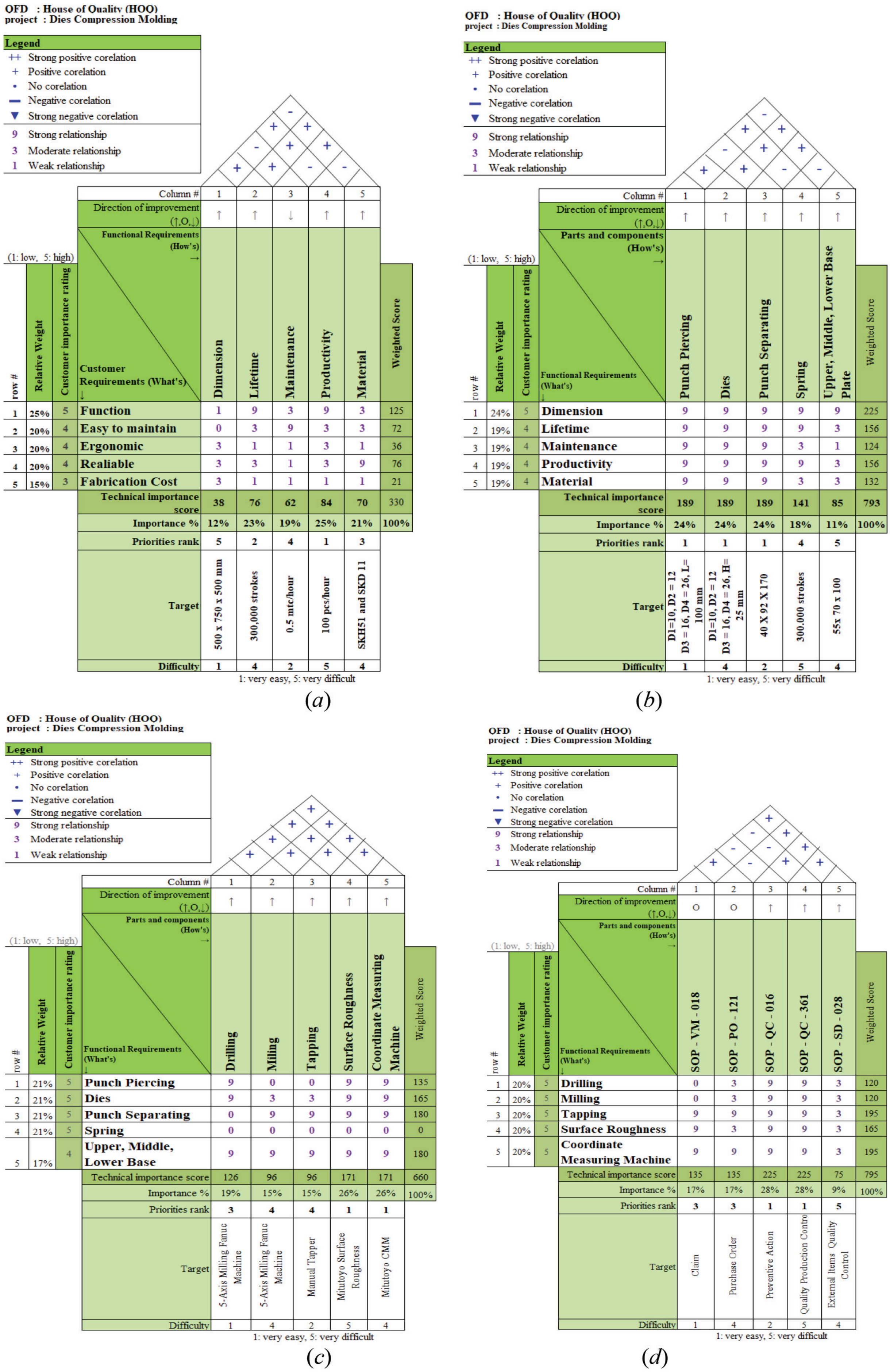

Figure 9. House of Quality (a) Phase 1 (Product Planning), (b) Phase 2 (Product Design), (c) Phase 3 (Process Planning), and (d) Process Control

to specify the scoring. The team makes a consensus about the scoring value of the relative weight, customer importance rating, technical importance score and importance, and the relation among technical importance. Scoring positive (+), neutral, and negative (-) notation indicates the correlation between functional requirements. For example, lifetime strongly correlates with material, so the correlation is positive (+). On the contrary, the dimension negatively correlates with material, so the score is negative (-). Meanwhile, for the relationship between customer needs and functional requirements (technical specifications), scoring 9 shows a strong relationship, 3 for moderate, 1 for weak, and 0 for no correlation. For example, in scoring, the function (customer requirement) strongly correlates with productivity and lifetime (functional requirement), so the scores are 9. On the contrary, the easy-to-maintenance weak correlates with dimension, so the score is 0.

The next stage calculates the sum of the weighted and technical importance scores by multiplying scoring values horizontally and vertically, respectively. The weighted score (horizontal) shows that function is critical (125 total score), followed by reliable (76 total score), easy-to-maintenance (72 total score), ergonomics (36 total score), and fabrication costs (21 total score). The technical importance score (vertical) shows that productivity is the most essential (84 total scores and priority rank 1), followed by lifetime (76 total scores and priority rank 2), material (70 total scores and priority rank 3), ergonomics (62 total scores and priority rank 4), and fabrication costs (38 total scores and priority rank 5). Meanwhile, difficulty assessment shows a scale of "very difficult" of 1 for dimension and "very easy" of 5 for productivity with a challenging difficulty level. This technical importance will be used as guidance in developing mold concepts.

The die-developing team then develops some die concepts based on the HOQ of QFD Phase 1 Die Planning results. Three alternative concepts of die system designs are proposed, as shown in Figure 10. Alternative 1, the die and punch holder, is a one-block casting part. The punch and button die used are standard parts and use SKD 11 materials with high hardness. The stopper is only one, so an unstable position is possible. The weakness is that maintenance is complicated because the block must be replaced if the die holder is damaged (cracks). Alternative 2, the punch holder, consists of a separating insert locator and a back plate to make machining and maintenance easier. The insert locator will make it easy to attach and remove so that only the damaged part must be replaced when damage occurs. In addition, the construction uses two types of stoppers, namely stopper plate and stopper pin, so that the position of the stock plate is more stable during processing and the potential for burrs can be reduced. The weakness of this concept is less in dampening vibrations.

Alternative 3, the die and punch holder are casting parts in one block, the same as alternative 1. Meanwhile, the construction uses two types of stoppers, the same as alternative 2. This alternative is better at dampening vibrations. The drawback of this concept is that only if the die holder is damaged must one block be replaced. Therefore, it is difficult for the treatment process. Those three designs have been screened and scored by forming group discussions, and alternative two is selected. Productivity, lifetime, material, ergonomics, and fabrication costs are the concept scoring criteria. Alternative 2 will continue to the next die-developing steps.

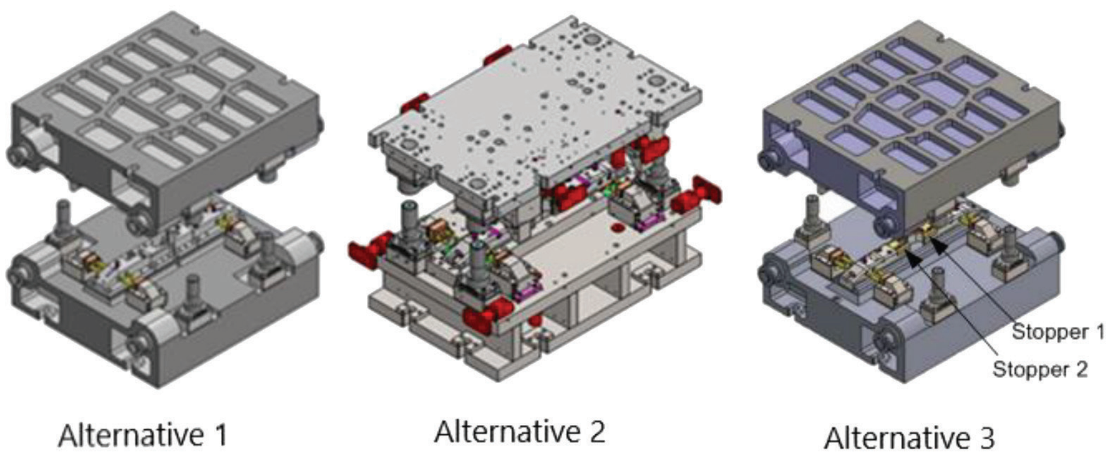

Figure 10. Three Alternative Designs

Figure 11 below details the new punch and dies system's selected concepts (Alternative 2). In addition, some advantages of this selected alternative are that the design is easy to maintain, good ergonomic and safety aspects, low manufacturing cost, and reliability. The die design also considers the standard computation for punch and dies dimension based on the cutting forces needed to increase reliability. This alternative is also based on the target data in HOQ of QFD Phase 1.

Phase 2 of the HOQ product design is shown in Figure 9 (b) above. In this phase, the functional requirements of the die produced in Phase 1 of QFD (Matrix I) are translated into more detailed quality characteristics of parts (Matrix II). The concept of parts, including engineering characteristics, is created during this stage. In this phase, the development team also implements brainstorming in a focus group discussion to complete the QFD die design matrix II. The technical requirements for the second HOQ level are part characteristics placed at the top of the design deployment matrix. Based on the RCA, critical parts of the dies set, such as punch piercing, dies, punch separating, spring, upper base plate, middle base plate, and lower base plate, are placed on the top of this matrix. Therefore, the designer then estimates the engineering of each part's characteristics. The analysis includes punch piercings with 10 mm, 12 mm, 16 mm, and 26 mm diameters and a punch length of 100 mm.

Similarly, the diameter of the die follows the diameter of the punch with a height of 25 mm. It can also be seen that the punch separating has dimensions of 40 mm x 92 mm x 120 mm, and the base plate on the dies with dimensions of 55 mm x 70 mm x 100 mm. The cutting force is calculated using Equation 1. For one part, if the circumference of the overall cutting length (piercing, two holes cam-piercing and separating) is 673.73 mm, the plate thickness is 4.5 mm, and the yields strength of the plate is 308 MPa, the cutting force, Ps, is 933.80 kN (95 ton). For two parts, cutting forces become twice, 1,867.60 kN. The press capacity to be used with safety factors 1.5, by using Equation 2, is 2,241.12 kN (228.53 ton). Therefore, the capacity of the AIDA press machine, which is 1,000 tons, is very safe for this die stamping.

The punch length is calculated correctly to ensure the construction of the punch is safe. It can be determined by using Equation 5. The moment of inertia, I_x, can be calculated by the standard equation for a circle $\left(I_x = \frac{\pi d}{64}\right)$, where d is the diameter of the punch. The computation result of the moment of inertia is presented in Table 4. If modulus elasticity, E, of steel, is 210 GPa and c is 2 for heat-treated steel, the length of punches for each diameter is tabulated in Table 4. Misumi standard is used as raw material for punch piercing and cam piercing.

The dimension of the button dies, including die diameter, d_m, and height, h was calculated based on the size of the punches, d_p, used. Button dies diameter is calculated by using Equation 8. For Example, if the thickness of the plate to be cut is 4.5 mm (more than 3 mm), coefficient k is 0.01, and the ultimate tensile strength (UTS) of SAPH440 steel is 305 MPa, clearance, C, calculated using Equation 4, is 0.461 mm. Therefore, $d_m = d_p + 2C = 10{,}921$ mm. The height of the dies is calculated using Equation 7. The whole calculation is tabulated in Table 6 as follows. After calculations are obtained, the dimensions of the standard button die from Misumi for dies piercing and cam piercing can be seen in Table 5.

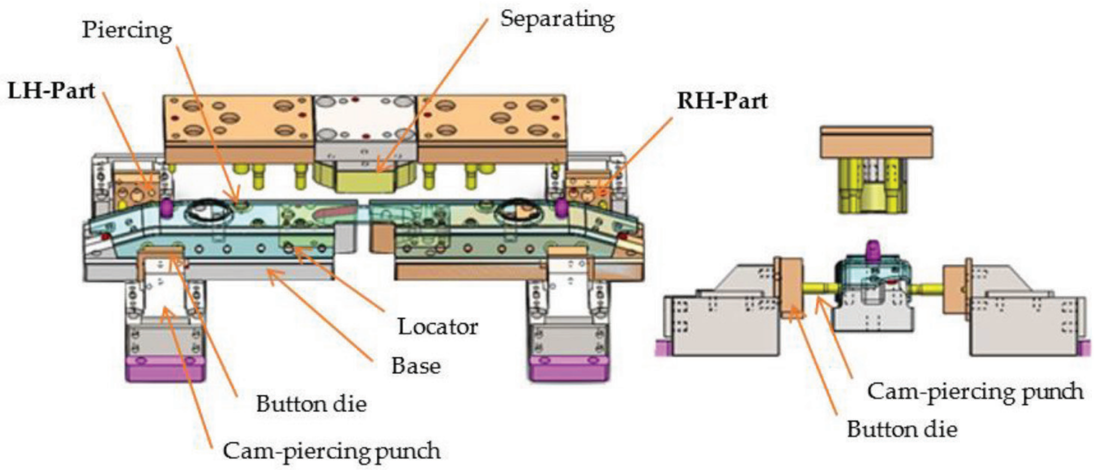

Figure 11. Selected Design

Table 4. Punch Length

No.	Type Punch	Diameter Punch, d_p (mm)	Moment of Inertia (mm^4)	Punch Length (mm)	Misumi standard**), L (mm)
1	Piercing	10	490.8	45	60, modified into 45*)
2	Piercing	16	3,216.9	80	60, modified into 58*)
3	Piercing	25.9	22,088.6	184	80
4	Cam-piercing	12	1,017.8	58	100

*) Modified is needed to avoid buckling
**)Type AP and APH, Type Length S, Shape tip type A

Table 5. Die Button Dimensions

No.	d_p (mm)	d_m (mm)	h computation (mm)	*Misumi* Standard of h (mm)
1	10	10.92	16.50	25
2	12	12.92	17.50	25
3	16	16.921	19.30	25
4	25.9	26.82	22.60	25

In Phase 3 of the QFD process requirements (Figure 9 (c) above), the matrix input is obtained from the previous matrix output of Phase 2. This level includes translating each part's quality characteristics into manufacturing characteristics. The procedure for process planning is a table or list that contains a checklist of each step in manufacturing planning. The processes include drilling, milling, tapping, surface roughness, and dimension and tolerance measuring. At this level, several targets exist, such as drilling and milling with 5-axis milling, tapping with a manual tapper, surface roughness with a surface roughness tester, and dimension and tolerance using coordinate measuring machines (CMM). Phase 3 is necessary because each part processed must be appropriate to the design target. In addition, it can also be determined whether the parts are fabricated internally or externally. All parts are fabricated and assembled based on this HOQ matrix III in Figure 9 (c). The final assembly of the core side is shown in Figure 12.

In Stage 4 of QFD (Figure 9 (d) above), the HOQ creates relationships and aligns between the process characteristics of QFD phase 3 and the process control. Decision-making is carried out to improve production output. Furthermore, work instructions are commonly used in production planning to monitor production processes, schedule maintenance, and train operators. At this stage, targets are defined, including claims, purchase orders, preventive actions, quality production control, and external item quality control. In this stage, the process is tested and inspected related to the critical dimension of the LH-part and RH-part to check the die quality and reliability. The critical dimensions include the lower dimension (Lo), upper distances (UP), and check burr, as shown in Figure 13. The measuring included before and af-

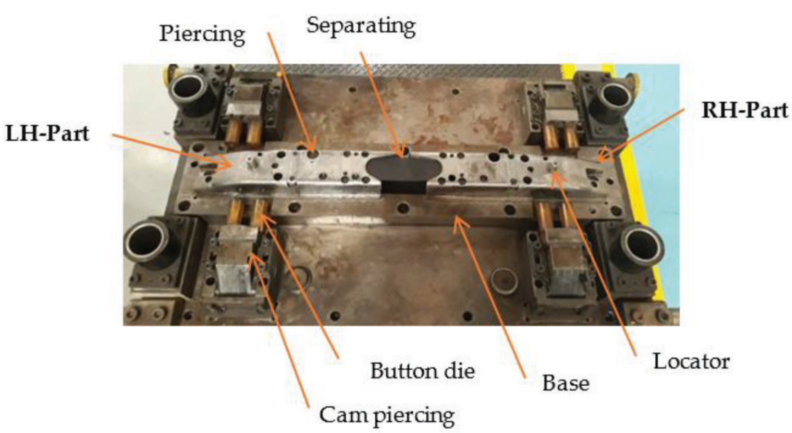

Figure 12. Final Dies Results (Core Side)

ter the design. The following is the data from the dies piercing, cam piercing, and separating test in Table 6, accomplished 30 times in regular production.

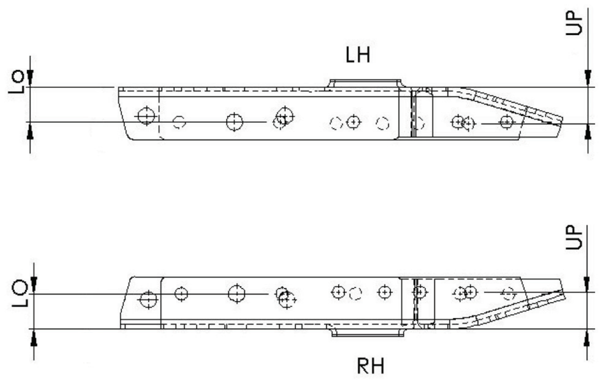

Figure 13. Press Part: Part LH (top) and Part RH (bottom)

Based on data tests in Table 6, it concludes that die produces high-quality products without burr finding in the piercing, cam-piercing, and separating process, and 100% of parts meet the standards according to product planning. Furthermore, these designed dies using the QFD method have several advantages compared to the old one. These dies are easy to maintain because they use button-type dies. Die parts can be replaced more easily if one punch or dies is broken or worn without changing the overall die system. On the other hand, the old one that uses one block of dies is difficult to change parts. The new system also has good ergonomic aspects because the operator can safely operate and maintain these dies. The manufacturing cost of the new one is lower than the old design because of not having one block system. It has high durability, a 10,000-stroke lifetime, and productivity of up to 100 pieces/hour.

Table 6. Deviation of dimensions assessment and burr on the RH part

No.	Before (Old Die)				After (New Die)			
	UP ± 0.70 mm	LO± 0.70 mm	Burr	Result	UP ± 0.70 mm	LO ± 0.70 mm	Burr	Result
1	0.58	0.35	no	Good	0.44	0.67	no	Good
2	0.64	0.63	yes	Rework	0.48	0.69	no	Good
3	0.67	0.73	yes	Rework	0.48	0.67	no	Good
4	0.47	0.63	yes	Rework	0.48	0.67	no	Good
5	0.57	0.93	yes	Rework	0.46	0.67	no	Good
6	0.67	0.4	yes	Rework	0.43	0.64	no	Good
7	0.62	0.41	yes	Rework	0.5	0.65	no	Good
8	0.38	0.42	yes	Rework	0.46	0.55	no	Good
9	0.36	0.63	yes	Rework	0.47	0.63	no	Good
10	0.57	0.64	yes	Rework	0.45	0.63	no	Good
11	0.58	1.05	yes	Rejected	0.4	0.63	no	Good
12	0.52	1.06	yes	Rejected	0.4	0.12	no	Good
13	0.41	0.47	yes	Rework	0.4	0.64	no	Good
14	0.55	0.84	yes	Rejected	0.57	0.54	no	Good
15	0.76	0.49	yes	Rework	0.56	0.38	no	Good
16	0.63	0.5	yes	Rework	0.41	0.64	no	Good
17	0.72	0.51	yes	Rework	0.45	0.42	no	Good
18	0.33	0.52	no	Good	0.36	0.54	no	Good
19	0.62	0.53	yes	Rework	0.38	0.64	no	Good
20	0.71	0.54	yes	Rework	0.38	0.54	no	Good
21	0.7	0.55	yes	Rework	0.37	0.64	no	Good
22	0.68	0.56	yes	Rework	0.4	0.22	no	Good
23	0.55	0.57	no	Good	0.42	0.22	no	Good
24	0.75	0.58	yes	Rework	0.38	0.38	no	Good
25	0.66	0.59	yes	Rework	0.43	0.38	no	Good
26	0.44	0.6	yes	Rework	0.42	0.38	no	Good
27	0.55	0.61	yes	Rework	0.39	0.42	no	Good
28	0.63	0.62	yes	Rework	0.46	0.46	no	Good
29	0.49	0.63	no	Good	0.42	0.5	no	Good
30	0.24	0.64	yes	rework	0.4	0.54	no	Good
Min	0.24	0.35			0.36	0.12		
Max	0.76	1.06			0.57	0.69		
Average	0.57	0.61			0.44	0.52		
Good	13%				100%			
Rework	87%				0%			

Note Part RH Deviation, Standard: ± 0.70 mm

5. Conclusions

Compound die design was designed and manufactured in this work based on the QFD method. The redesign process consists of problem identification; root causes analysis of defects; redesign planning based on the QFD phase 1; developing and selecting die concept; parts design using QFD phase 2; parts fabrication and assembly using QFD Phase 3; and testing the result for monitoring output using QFD Level 4. The die design needs involved functional aspects, ease of maintenance, ergonomics, reliability, and lower manufacturing cost. Engineering aspects include calculating die and punch geometry, size, clearance, and material selection based on the industrial standard.

Based on the result, it concluded that the design dies meet the requirements and the standards. It produces high-quality products without burr finding in the piercing, cam-piercing, and separating process and 100% good products because all stamping products meet requirements according to the check plate's tolerances. It also increases productivity because part rejects decrease from 87% to 0%. The die is also easy to maintain because it uses button-type dies, so there is no need to change if the die is broken. The dies also have good ergonomic aspects because the operator can operate and maintain molds and punches safely and faster. It concluded that QFD can be applied effectively in this work.

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