J. Electrical Systems 20-3 (2024): 33-42

[1,*]Shaohua Hu
[2]Shenghao Li

Design of Automatic Seaming Machine for Fire Air Ducts with 3D Model and Its Experiment

Journal of Electrical Systems

Abstract: - The fire air duct is one of the important components of the ventilation system in large buildings, which is is a unit system for ventilation and smoke exhaust. The ventilation system is a customized system with a wide range of applications and a high demand, resulting in the use of multiple sizes and specifications of fire air ducts. At the same time, fire air ducts are generally made of thin galvanized iron sheets, which have poor rigidity and are prone to deformation. For the two above-mentioned reasons, the seaming process of the fire air duct is currently mainly completed by manual tapping, resulting in low processing efficiency, high labor intensity, and high cost. Therefore, it is necessary to design an automated equipment that can complete the fire air duct seaming process. Firstly, a 3D model for automatic seaming machine for fire air ducts to demonstrate the working principle and a double head positioning and clamping mechanism is proposed to improve the pipe rigidity; Secondly, to adapt to most specifications for rectangular fire air ducts, a system was designed that utilizes the two right angle ends of the stitching edge for positioning and clamping without many special toolings. Thirdly, a set of automatic seaming prototype has been manufactured based on the above design ideas. The experimental results on the prototype show that the fire air duct automatic stitching machine can seam a fire air duct within 1 minute. Compared with manual processing, the processing efficiency is improved by more than 80%.

Keywords: 3D Model, CAD, Fire Air Duct, Automated Equipment, Machine, Rolling, Clamping.

I. INTRODUCTION

Ventilation ducts, also known as fire air ducts, are very common equipment in large buildings such as hospital, chemical plant, large shopping mall, underground parking, and so on. Their main functions are ventilation, air exchange, and smoke exhaust. Fire air ducts for general ventilation are the main method to control particulate matter and improve indoor air quality [1, 2]. Fire air ducts are generally processed from galvanized steel plates into rectangular or circular ducts. The current processing procedures for fire air ducts mainly include blanking, punching, flanging, biting (also known as seaming), and flange riveting[3].Blanking, punching, and flanging have achieved mechanized or automated processing, while seaming and flange riveting are still done manually. Due to diverse specifications and the characteristics of the plates being thin and easily deformable, it’s challenging to automate the seaming process. But given its low efficiency, high labor intensity, and poor processing quality, it becomes a bottleneck in the process, urgently needing automation.

Fire air duct’s manufactruting process represents a typical sheet metal forming process. Current research on sheet metal processing technology mainly focuses on following procedures including blanking, bending, drawing, punching, flanging, and biting. The sheet metal forming process of forming tools is cost- and labor-intensive. The main reason for this is the high complexity of interaction between forming machine, tool structure, and process, which is currently only partially taken into account in simulations and during tool tryout [4,5].The utilization of numerical simulations to predict sheet metal forming process of ultra-high strength TRIP steel HCT690T EN 10346[6].In the numerical simulation, the basic deformation computation of the material for the stamping and the simulation of the material spring-back that occurs after releasing the loading force of punch are performed. To prove the validity of the numerical simulation results or to perform the so-called compensation, the numerical simulation contour of the stamping is finally compared with the real contour [7-9]. As can be seen from the above, simulation technology has become very mature in sheet metal processing and has been widely applied.

At the same time, there are many mature sheet metal processing technologies that have been widely applied. On the one hand, blanking is the most widely used forming operation. It is used both for the preparation of semi-finished products and cutting of metal parts either for final use or as preparation for other technological operations [10]. Simple analytical calculations are usually used during preparation of serial manufacturing [11]. These analytical calculations are sufficient for determining basic parameters of blanking process as maximal blanking force, however when problems occur during the manufacturing process the solution is often complicated and can be calculated only by using advanced numerical methods [12]. On the other hand, flanging and biting have also

---

[1] School of Intelligent Manufacturing and Transportation, Chongqing Vocational Institute of Engineering, Chongqing; 402260, China
[2] School of Intelligent Manufacturing and Transportation, Chongqing Vocational Institute of Engineering, Chongqing; 402260, China
*Corresponding author: Shaohua Hu

partly achieved automation or mechanized processing [13-15]. However, the duct sheet metal forming process is not the difficulty of manufactruting process of fire air ducts. The difficulty of processing lies in assembly process, which makes two thin sheet metal parts bite together without internal support. The seaming process of the fire air conduct is a typical assembly process that still be manually finished due to varying dimensions, easily deformable plates, and other factors [16]. According to on-site data statistics on current manual processes, seaming a work-pieces takes approximately 5 to 10 minutes. if the time for flange plate punching and riveting is considered, the average time of making a piece of fire air duct is about 32 minutes.Therefore, Hu Shaohua and others proposed integrated side-seaming and edge-rolling techniques, but the mechanism design is complex and costs are high, which leads to restrict its application [17].

Hence, researching automatic seaming and automatic riveting equipment is essential. This study proposes a simple design of the automatic seaming machine. A 3D model for automatic seaming machine for fire air ducts to demonstrate the working principle, which is composed of dual-head positioning and multi-pass roll-pressing, that can automatically seam the air ducts with simple operations and high processing efficiency. The rest of this paper will be organized as follows: in section 1, fire duct automatic seaming process and its performance indicators are proposed according to analyzing current manual process; in section 2, how to design the Automatic Seaming Machine is stated in detail; in section 3, experiment and its result on the prototype is given; in section 4, conclusion and the next stage of research is stated.

II. Fire Air Duct Seaming Process and Performance Indicators

A. *Traditional Seaming Process of Fire Air Duct*

The production of fire air ducts is a typical sheet metal processing process. The process mainly includes cutting, bending, punching, stitching, and flange welding. The cutting and bending processes have been automatically fininshed by some specialized machines. The stitching process is essentially an assembly process, and achieving automated production is extremely difficult due to the processing characteristics of the air duct itself. At present, the stitching of fire air ducts is mainly done manually at the installation site. In the stitching process, a man use a steel hammer to bend one edge 90 degrees and fit it onto the other side, then use a hammer wrapped in rubber to correct the plane to be smooth. This process requires hundreds of strikes, which is labor-intensive and inefficient. Rectangular fire air ducts typically use 1-piece or two-side biting methods in Figure 1, and during duct jointing, wooden or plastic non-metallic hammers should be used. Although this method ensures even local stress and a certain degree of flatness, its efficiency is extremely low. There are two main processing methods for rectangular fire air ducts: the first method, as shown in Figure 1, is to bend a sheet metal body 1 to form a cross-sectional state, then to curled part 2, sewing card slot 3, and sewn card plate 4, respectively. The sewn card plate 4 is inserted into the sewing card slot 3, and then the curled part 2 is bent from state a to state b to obtain state c in Figure 2, At this point, the edge of the curling edge will clamp the sewing card board onto the sewing card slot of the sheet metal bending plate to complete the sewing; the second method is to sew two halves of the "L" shaped sheet metal bending plate together, the principle is the same as the previous one, but it needs to be sewn diagonally on both sides, requiring two side stitches. At present, the side stitching of fire air ducts relies on manual work. Generally, a hammer is used to strike the curled edge and bend it to fit the edge of the curled edge. Finally, the stitching part is repaired flat. This method is inefficient and labor-intensive; At the same time, manual operation cannot guarantee the consistency of product quality. Therefore, there is an urgent need to use automated equipment to complete this process.

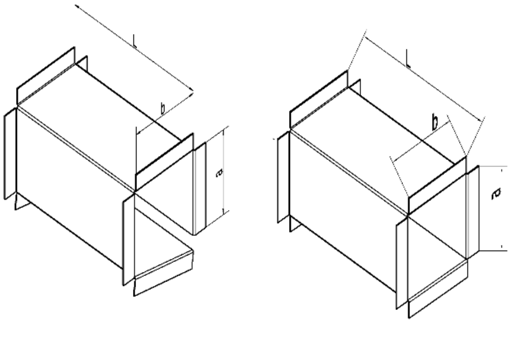

Figure 1: Duct Schematic Diagram (Before Seaming and After Seaming)

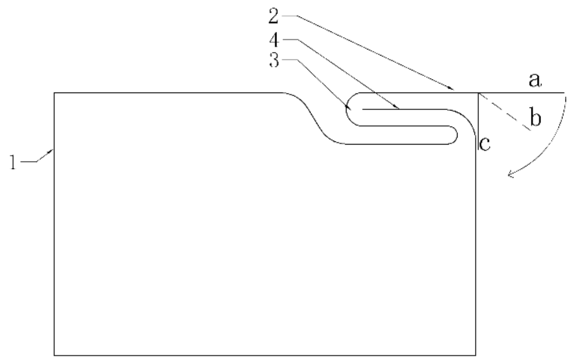

Figure 2: Duct Seaming Schematic Diagram
(1- Sheet metal body, 2- Curled part, 3- Sewing card slot, 4- Sewing card plate, from state a to state c)

B. Fire Air Duct Automatic Seaming Process Performance Indicators

As mentioned in section 2.1, the failure to achieve automated processing in the stitching process of fire air ducts is determined by the characteristics of the product itself, mainly in the following two aspects.

The first characteristics is that duct rigidity is low and easily deformable. As usually, the duct wall thickness is from 0.75mm to 1.5mm but its length is above 1200mm, which makes the duct deformable.

The second characteristics is that the specifications of duct are diverse. The long and short sides of the cross-section of the air duct vary between 200-2000mm, respectively. At the time, the length of the air duct should be selected in the range of 1200-1500mm. The specific size is selected based on the air volume, resulting in a variety of specifications. Excessive specifications are detrimental to the design of automation equipment.

Due to the thinness of the duct wall, using simulated manual hammering or rolling shaping can easily cause deformations leading to scrapped products. If support tooling is introduced inside the duct to increase rigidity, the support mechanism is long (1200-1500mm), demanding substantial room for operation, making it cumbersome and inefficient. Therefore, the overall design requirements for the device are: First, simple operation without the need for complex supporting structures or tooling; Second, cover as many product specifications as possible to enhance equipment applicability.

After on-site process research and trial experiments, and considering the complexity of the equipment, the initial automatic seaming process is established as follows: pre-processing → manual duct placement → automatic seaming → manual duct removal. Pre-processing refers to manually combining two parts before placing the duct and pre-folding both ends to ensure product stability and successful seaming by the equipment. The performance indicators required for the automatic seaming device of fire ventilation ducts are:

(1) The device should be simple and easy to maintain. Single-piece processing time (including preparation) should not exceed 2 minutes.

(2) Duct seaming time should be less than 30 seconds per side.

(3) Suitable for ducts with material thicknesses of 0.75-1.5mm; processing dimension is $b \leq$2000mm, $a \leq$ 1500mm; $l \leq$1500mm.

(4) The product failure rate should be less than 1‰.

III. Design of the Automatic Seaming Machine for Fire Air Ducts

A. Overall Structural Design with 3D Model

To demonstrate the working principle, the 3D model of fire air duct automatic seaming machine is first built that consists of six parts, as shown in Figure 3, includes a hydraulic station, Electrical control cabinet (including touch screen, servo controller, PLC, etc.), upper and lower positioning devices (clamping mechanisms), travel adjustment device, and rolling wheel set, expectively. Through the 3D model (as in figure 3), we can easily see how the air duct stitching machine works. The air duct is positioned by the upper and lower clamping mechanisms, and then rolled into shape by rollers. Moreover, we can adjust the 3D model to see if there is any interference between the components and if the stitching meets the requirements. Through 3D modeling, it is possible to avoid losses caused by design errors using software alone without the need for physical equipment. Among them, the hydraulic station provides power for the upper and lower clamping mechanisms and the rolling wheel group's hydraulic motor; Electrical control cabinet mainly provides power supply and control logic for the travel adjustment servo motor, hydraulic controller, and pump station; the upper and lower positioning devices are mainly used for duct positioning and clamping; the travel adjustment device is mainly used to adjust the upper positioning device for processing ducts of different lengths; the rolling wheel group component provides rolling pressure to press the seaming part, thereby processing the seamed edge.

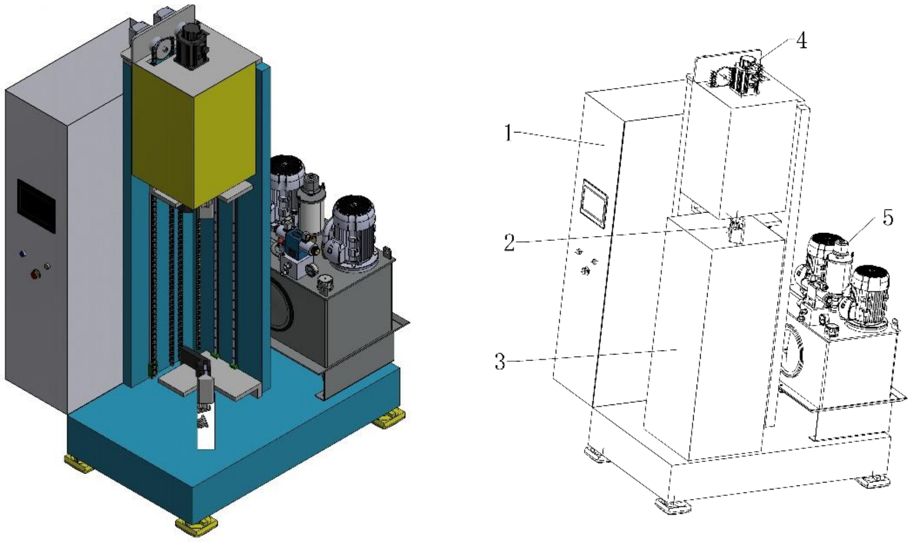

Figure 3: Structural Diagram of the Automatic Seaming Machine for Fire Ventilation Ducts (The Left is 3D Model)
(1- Electric Control Cabinet, 2-Positioning and Tightening Mechanism, 3- Rolling Wheel Group (Built-in), 4- Positioning Mechanism, 5- Hydraulic Station)

B. *Design of the Clamping and Positioning Mechanism*

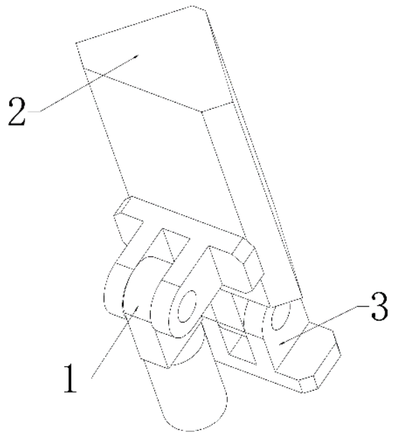

Figure 4: Fire Duct Positioning and Clamping Mechanism
(1- Clamping Head Oil Cylinder, 2- Clamping Head, 3- Clamping Head Fixed Shaft)

The duct clamping mechanism, as shown in Figure 4, mainly serves two purposes: the first is to position and fix the side of the duct in a straight line, facilitating roller edge forming; and the second is that the clamping head is embedded inside the duct to act as support, enhancing the duct’s rigidity. The clamping device primarily consists of the clamping cylinder and clamping head. The cylinder’s extension and retraction allow the clamping head to swing between 0° and 90°, achieving duct clamping and release. The shape of the pressing head is shown in Figure 5, where the right-angle part tightly adheres to the duct’s inner corner during clamping. Once the duct is positioned, the cylinder pushes the clamping block to swing, automatically clamping it. This setup accommodates the positioning of a full range of products without changing tooling. Given the duct wall is only 0.8-1.5mm thick and easily deformable when rolled, and since the entire internal support mechanism is large, requiring ample operational space and making it cumbersome, the pressing head’s design extends its length. Considering the most common duct length of 1200mm, both ends utilize dual pressing heads for support, reducing the direct rolling interval without duct support.

Based on the process experiments (Tab. 1), it's evident that with a single-side clamping head length of 300mm, the rolling pressure required is minimal under the thinnest wall thickness (0.75mm), but it's also most susceptible to deformation. Tests show that at 3Mpa pressure, edge rolling is formed without wall deformation for the thinnest wall; and at the thickest wall (1.5mm), edge rolling is achieved at 5Mpa without wall deformation. Under this clamping head size, there's no interference, and most product specifications can be processed without interference.

Table 1: Process Test Results (L=1200mm)

Single-side Clamp Head Length (mm)	Wall Thickness (mm)	Pressure (Mpa)		
		3	4	5
100	0.75	Cannot roll edge, no deformation	Can roll edge, with deformation	Can roll edge, with deformation
	1.5	Cannot roll edge, with deformation	Can roll edge, with deformation	Can roll edge, with deformation
200	0.75	Cannot roll edge, no deformation	Can roll edge, with deformation	Can roll edge, with deformation
	1.5	Can roll edge, with deformation	Can roll edge, with deformation	Can roll edge, with deformation
300	0.75	Can roll edge, no deformation	Can roll edge, no deformation	Can roll edge, no deformation
	1.5	Can roll edge, no deformation	Can roll edge, no deformation	Can roll edge, no deformation
400	0.75	Can roll edge, no deformation (partial interference)	Can roll edge, no deformation (partial interference)	Can roll edge, no deformation (partial interference)
	1.5	Can roll edge, no deformation (partial interference)	Can roll edge, no deformation (partial interference)	Can roll edge, no deformation (partial interference)
>500		Interference	Interference	Interference

C. Duct Height Adjustment Mechanism Design

The height adjustment mechanism is shown in Figure 5. Changes in the duct's height are set via the human-machine interface. The top servo motor elevates the upper clamping mechanism via a screw mechanism to accommodate ducts of varying lengths. The linear guide rail on the left is the motion mechanism for the upper and lower clamping mechanism and the roller mechanism, aligning all three mechanisms in one straight and parallel line, ensuring that the side rolling is smooth and straight.

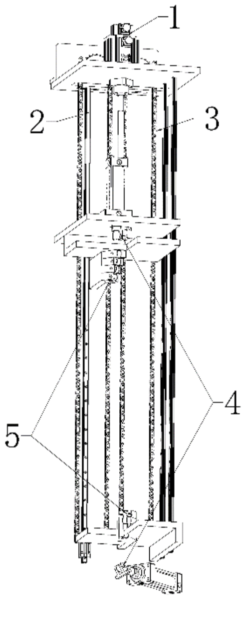

Figure 5: Fire Duct Height Adjustment Mechanism (Including Rolling Wheel Group)
(1-Servo Motor, 2- Guide Rail, 3- Transmission Chain of Rolling Wheel Group, 4- Positioning and Clamping Mechanism, 5- Rolling Wheel Group)

D. Seaming Roller Mechanism Design

In Figure 6, the roller mechanism employs alternating top and bottom rollers pressing from both sides towards the center. There is an overlap of about 100mm in the center, so sequential rolling is used. The rolling wheel is driven by a hydraulic motor, connected by chain transmission. Hydraulic drive has the advantages of high power and low noise. To reduce wall pressure and deformation during rolling, rollers are used sequentially. After calculations and considering the size of the mechanism, 4 rollers are used to press the side at angles of 15°→45°→75°→90°.

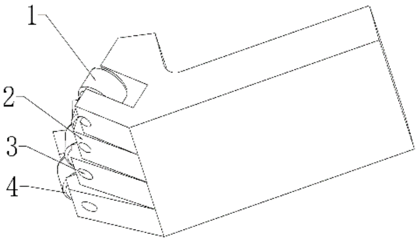

Figure 6: Sewing Roller Group Mechanism
(1-15 Degree Rolling Wheel, 2-45 degree Rolling Wheel, 3-75 Degree Rolling Wheel, 4-90 Degree Wheel)

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Experiments on Prototype and the Result Discussion

Based on the design proposed in this article, a prototype was fabricated as in Figure 7. The primary working process and functionality of the prototype are as previously described in section 2.2, with automatic side seaming resulting in high-quality processing. As shown in Figure 8, the automatic seaming is smooth and even, without wrinkles, while manual processing shows uneven hammering marks every 10-20mm.

Figure 7: Automated Seaming Machine Prototype

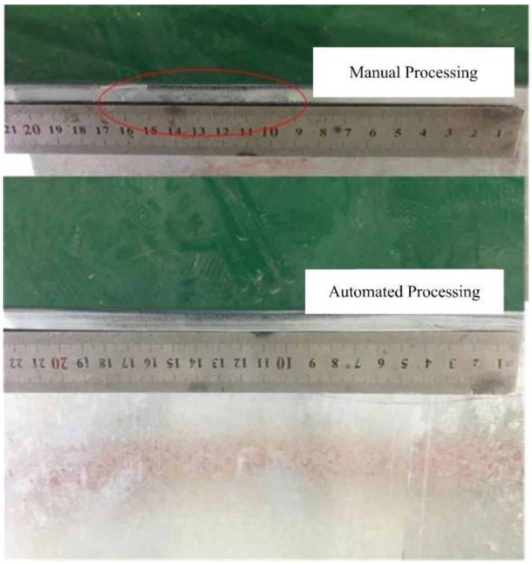

Figure 8: Comparison of Processing Quality

Table 2: Prototype Verification Experimental Data and Results

No.	Duct Specifications(mm)				Automated Processing Time(s)	Manual Processing Time(s)[1]
	b	a	l	δ		
01	250	120	1200	0.75	30	300
02	250	250	1200	0.75	30	300
03	320	160	1200	0.75	30	300
04	320	320	1200	0.75	30	300
05	400	200	1200	0.75	32	330
06	400	400	1200	0.75	32	330
07	500	200	1200	0.75	32	330
08	500	320	1200	0.75	32	330
09	500	500	1200	0.75	32	330
10	520	500	1200	0.75	32	350
11	630	250	1200	0.75	32	350
12	630	400	1200	0.75	32	350
13	630	630	1200	0.75	32	350
14	800	320	1200	1.0	40	500
15	800	630	1200	1.0	40	500
16	800	800	1200	1.0	40	500
17	1000	320	1200	1.0	40	500
18	1000	500	1200	1.0	40	500
19	1000	1000	1200	1.0	40	500
20	1250	400	1200	1.2	50	600
21	1250	630	1200	1.2	50	600
22	1250	1000	1200	1.2	50	600
23	1600	500	1200	1.5	65	800
24	1600	800	1200	1.5	65	800
25	1600	1250	1200	1.5	65	800
26	2000	800	1200	1.5	65	800
27	2000	1000	1200	1.5	65	950
28	2000	1250	1200	1.5	65	980

Note: 1. Manual processing time is the average time taken for a skilled worker to continuously process 10 products.

Using this prototype, processing experiments were carried out on 28 common specifications of rectangular ducts made of galvanized iron sheet. As shown in Table 2, the length of the air duct is fixed at 1200mm. By the orthogonal experimental method, the length, width, and iron sheet thickness are used to select 28 common specifications for comparative experiments. The comparative indicators are processing efficiency and processing quality. These 28 specifications of air ducts basically contain more than 80% of the quantity of common air ducts, so they are very representative. The differences in these experimental results can to some extent represent the quality and efficiency differences between the two methods in all duct processing. It is worth mentioning that the manual processing time is calculated based on the average completion time of 10 pieces because the manual processing time is different at every experiment.

The results are shown in Table 2, based on the thickness of the iron sheet 28 specifications of air ducts can be processed and divided into 4 groups: 0.75mm, 1.0mm, 1.25mm, and 1.5mm, expectively. This is because the thicker the iron sheet, the more difficult it is to manually process, which has the greatest impact on the time and quality of manual processing. In the 0.75mm group(No. 01-13 experiments), the automated processing time is from 30 seconds to 32 seconds while the manual processing takes between 300 seconds and 350 seconds. The time for both processing methods increases slightly with the increase of cross-section. This is because the larger the cross-section, the poorer the rigidity of the air duct, and the manual force should not be too strong to avoid deformation of the air duct, resulting in an increase in processing time. Automated processing equipment has a shorter processing time for air ducts with small cross-sections due to their good rigidity and high rolling speed. In the 1.0mm group (experiments 14-19), the automated processing times is 40 seconds and the manual processing takes between 500 seconds and 600 seconds. The automation time for the 1.2mm group (experiments 20-22) and the 1.5mm group (experiments 23-28) is 50 seconds, and the manual processing time is between 600-980 seconds. The increase in time for these three types of automatic processing and manual operation is the same as the 0.7mm group.

From Tab. 2, it can be seen that the automated processing time for each piece varies from 30s to 65s. For larger-sized ducts, the pre-processing and flipping times are longer, unrelated to wall thickness. Manual processing times are longer, ranging from 300s to 950s. Processing time is related to both duct size and wall thickness, with wall thickness having the greatest impact. Data in Figure 9 indicates that the efficiency of automated seaming has increased by at least 88.6% (800*320/630/800), and for other specifications, it’s above 90%.

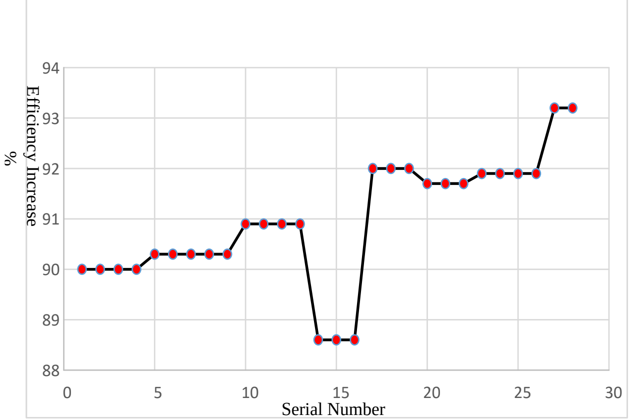

Figure 9: Enhancement in Automated Seaming Efficiency

Note2. Efficiency Increase = (Traditional Manual Processing Time - Automated Processing Time) / Traditional Manual Processing Time * 100%

B. Discussion about Seaming Roller Group Design

Multi-roll forming is a common sheet metal processing process. According to the number of rollers, the roll bending process can be divided into three forms, namely two rolls, three rolls, and four rolls [10]. Scholars have conducted extensive research on the relationship between forming curvature, bending, defect formation, and structural optimization for different forms of rolling processes using theoretical analysis, numerical simulation, and experimental research methods [18,19]. A large number of automated equipment are applied to sheet metal bending processes to improve processing efficiency [20]. If multi roll bending forming equipment is directly used, it will lead to very complex equipment and low efficiency. The structure of the fire air duct determines that the processing method of multi roll internal and external support rolling forming cannot be used [21]. The particularity of the fire air duct structure lies in that the sewn fire air duct is a relatively enclosed space (with closed surroundings and open ends). If the stiffness of the fire air duct is increased through internal support at both ends, it will result in two shortcomings: 1) the movement distance of the support fixture is at least twice the length of the fire air duct, the length (or height) of the processing equipment is increased by at least twice, and the volume of the equipment will also increase by at least twice; 2) When processing, it is necessary to replace the tooling. Taking into account the time required for changing the tooling and the movement of the tooling, the processing efficiency will be significantly reduced. Based on this, external support can only be used, while minimizing rolling pressure to avoid deformation of the fire air duct during processing.

V. CONCLUSION

This study firstly displayed a 3D model for automatic seaming machine using CAD that utilizes a dual-clamping multiple roller method for the automated seaming of ducts, which has been validated through a prototype. Through 3D modeling, it is possible to avoid losses caused by design errors using software alone without the need for physical equipment. Experimental results indicate that the device is suitable for the vast majority of duct products currently available in the market, showcasing high efficiency, low labor intensity, and user-friendly operation. The results reveal that duct seaming time is less than 1 minute, as opposed to approximately 5 minutes for manual processing, marking an efficiency improvement of over 80%. Additionally, the processing quality has also seen significant enhancement.

In the next phase, the research will expand in two directions: On one hand, integrating this equipment with the preceding and subsequent automated processes to form an automated production line, increasing overall processing efficiency and reducing labor intensity; on the other hand, developing a smaller-sized seaming device which is easy to transport to installation sites for on-site processing.

ACKNOWLEDGMENTS

This research was funded by the Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJQN202203408), the Science and Technology Research Key Program of Chongqing Municipal Education Commission (Grant No. KJZD-K201903401), and the project fund of Chongqing Education Commission Group Innovation (Grant No. CXQT21032).

REFERENCES

[1] Li, Y., Chai, P., Wang, Y., Cheng, Z. Assessment of Chemical Fiber Air Filter for General Ventilation. *Atmosphere* 2021, 12, 1636.

[2] Koutrakis, P.; Briggs, S.; Leaderer, B. Source Apportionment of Indoor Aerosols in Suffolk and Onondaga Counties, *New York. Environ. Sci. Technol*. 1992, 26, 521–527.

[3] Behrens, B.A.; Bouguecha, A.; Krimm, R.; Matthias, T.; Czora, M. Consideration of the Machine Influence on Multistage Sheet Metal Forming Processes. In Process Machine Interactions; Denkena, B., Hollmann, F., Eds.; Springer: Berlin/Heidelberg, Germany, 2013; pp. 403–417.

[4] Tehel, R.; Päßler, T.; Mihm, M. Modeling elastic behavior of forming machine components to reduce tool manufacturing time. *Procedia Manuf.* 2019, 27, 177–184.

[5] Tehel, R.; Päßler, T.; Kurth, R.; Nagel, M.; Reichert, W.; Ihlenfeldt, S. Virtual Tryout: Case Study on Simulation-Based Design and Die Spotting of Forming Tools. *Eng. Proc.* 2022, 26, 9.

[6] Koreček D, Solfronk P, Sobotka J.Numerical Simulation as a Tool to Predict Sheet Metal Forming Process of TRIP Steel HCT690, *Manufacturing Technology*, 2020, 5, 625-631.

[7] JANDA, T., et al. Influence of Cooling Rate on Microstructure and Mechanical Properties of 42SiCr Steel after Q&P Process. *Manufacturing Technology*, 2019, 19(4), 583-588.

[8] CHOVANEC, A., BREZNICKÁ, A. Some aspects of a manufacturing process simulation. *Manufacturing Technology*, 2017, 17(3), 319-325.

[9] SU, CHUNJIAN, WANG, XUETAO. Sprinkback Research of V-type Sheet Metal forming based on the Adjustable Drawbead and Variable Blank-holder Force Cooperative Control Technology. *Manufacturing Technology*. 2014, 14, 618-625.

[10] BLATNICKÝ, M., ŠTAUDEROVÁ, M., DIŽO, J. Numerical Analysis of the Structure Girder for Vehicle Axle Scale Calibration, *Procedia Engineering*, 2017,177, 510-515.

[11] KOPAS, P., JAKUBOVIČOVÁ, L., VAŠKO, M., HANDRIK, M. (2016). Fatigue resistance of reinforcing steel bars, *Procedia Engineering*, 2016,136, 193-197.

[12] ADAMUS, J., LACKI, P., WIECKOWSKI, W. Numerical simulation of the fine blanking process of sheet titanium, *Archives of Metallurgy and Materials*, 2011,56 (2), 431-438

[13] Neto, D.M.; Coër, J.; Oliveira, M.C.; Alves, J.L.; Manach, P.Y.; Menezes, L.F. Numerical analysis on the elastic deformation of the tools in sheet metal forming processes. *Int. J. Solids Struct*. 2016, 100–101, 270–285.

[14] Fang Xifeng.; Lu Beilei.;Zhu Chengshun.;Zhang Shengwen. Research and development of MES system based on sheet metal processing unit. *Manufacturing Automation*, 2019, 41(04): 19-23.

[15] Li, H.W.; Ren, G.Y.; Li, Z.J.; Feng, L.; Yang, H. Forming mechanism and characteristics of a process for equal-thickness in-plane ring roll-bending of a metal strip by twin conical rolls. *Mater. Process. Technol.* 2015, 227, 288–307.

[16] Hu Shaohua.; Luo Yuancheng.; Wang Nuhui.; He Xiaohui. A device for side seaming of fire air ducts. Chongqing: CN111672987A, 2020-09-18.

[17] Cao, H.; Yu, G.; Yang, C.; Zhao, J. Research on a Control Strategy of the Symmetrical Four-Roller Bending Process Based on Experiment and Numerical Simulation. *Symmetry* 2021, 13, 940.

[18] Zhao, W.; Liao, T.W.; Kompotiatis, L. Stress and Springback Analyses of API X70 Pipeline Steel Under 3-Roller Bending via Finite Element Method. *Acta Metall. Sin.* 2017, 30, 470–482.

[19] Kappis, L.V.; Karteusch, N.; Cramon-Taubadel, E.v.; Froitzheim, P.L.; Flügge, W. A Contribution to the Automation of Roll Bending of Heavy Plates by Upgrading Roll Bending Machines with Artificial Intelligence. *Eng. Proc.* 2022, 26, 3.

[20] Trzepieci ´nski, T.; Szwajka, K.; Szewczyk, M. An Investigation into the Friction of Cold-Rolled Low-Carbon DC06 Steel Sheets in Sheet Metal Forming Using Radial Basis Function Neural Networks. *Appl. Sci.* 2023, 13, 9572.

[21] Gao Jiaxin .; He Dongye.; Sun Lirong.; and et al. Prediction of Longitudinal Curvature Radius of 3D Surface Based on Quadratic Relationship between Strain and Coordinates in Continuous Roll Forming. *Metals* 2020, 10, 1249.