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Design and Implementation of Multi-Configuration Rolling Machine

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Abstract

For decades, metal corrugated sheets have usually been manufactured using conventional roll-forming machines with lower and upper rollers or a die and a press as the main shaping elements. However, these machines and their related processes present economic disadvantages because of additional expenses required to improve and manage forming tools. To overcome these drawbacks, reconfigurable machines, such as dedicated and flexible manufacturing systems, were used as alternatives; they possess high flexibility for accomplishing forming processes. Reconfigurable machines are designed around a particular family of manufactured outcomes, allowing for high system flexibility. In light of the latest developments in reconfigurable machine design, this study proposes a new sheet metal forming roller called the discrete multi disk roller (MDR) as an alternative to the traditional roller design. Unlike existing processes, the MDR minimises production costs associated with material loss and effectively decreases forming errors. Furthermore, it utilises multi-disk as reconfigurable rollers. The technique and applicable procedure of the MDR are described, and wavy sheets with different dimensions and shapes are formed to verify the applicability of the reconfigurable roller, a critical component in the forming process. Thirteen parts with different configuration profiles were produced using the proposed MDR machine.

Keywords: *machine design; reconfigurable machine; discrete multi-disk roller; reconfigurable manufacturing*

1. Introduction

Medium- and high-volume parts are currently produced by applying two conventional manufacturing techniques: dedicated manufacturing systems (DMSs) and flexible manufacturing systems (FMSs). DMSs are cost-effective for large production volumes and extended production durations, so they are intentionally used to produce a specific, unchanging part [1]. Conversely, FMSs are economical when the manufacturing quantities are limited, and large varieties of parts are produced, allowing for many design modifications to be made during production [2]. Nonetheless, the fast changes in market demands have rendered traditional DMSs impractical for many industrial applications, leading to a broader adoption of FMSs. However, the inability to achieve the same level of efficiency and robustness as in DMSs and the high resource wastage during production procedures have made FMSs uneconomical in many situations [3]. In response to these challenges, a novel approach to customised manufacturing was developed named reconfigurable manufacturing systems (RMSs). The major advantage of this new technique is the customised flexibility to produce a ‘part family’ of products at lower investment costs than FMSs [1]. Typically, RMSs incorporates conventional flexible machines and a new type of machine called the reconfigurable machine (RM) into its production line. RMs are designed around a specific part family of products and enable substantial changes in their structure. The idea behind RMs is to allow changes in machine configuration according to production requirements. RMs introduced a new methodology to bridge the gap between the high flexibility and high cost of totally flexible machines and the low flexibility and low cost of fully dedicated machines [1]. In addition, these systems are designed to accommodate a specific range of production requirements (i.e. product mix and volumes). RMSs are categorised according to their functional flexibility. They may be suitable for certain production requirements or economically replaced with a new set of production necessities. With the flexibility of combining the advantages of DMSs and FMSs such as production requirement customisation, resource minimisation and flexibility in their design, RMSs are considered an economical and robust solution for many industrial applications [4,5,6].

Several studies have focused on the rolling process using a dedicated roller die. Scientific literature on the reconfigurable rolling process (RRP) using a pin or punch-type tooling is limited. Yoon et al. [7,8,9,10] proposed a new sheet metal forming process named the flexibly reconfigurable roll forming (FRRF) as an alternative to existing processes. Unlike the conventional forming processes, FRRF can lower the production expenses resulting from material loss and minimise forming errors. Moreover, it uses a smaller apparatus, adjustable punches and upper and lower reconfigurable rollers to manufacture full-size blanks in the longitudinal direction, similar to the regular roll forming process. Wang et al. [11,12] designed a novel forming process for 3D surface parts that combines rolling with multi-point forming technology. This process employs a set of two forming rolls. The roll gap of the forming rolls has a non-regular distribution which, when controlled, leads to a residual stress pattern in the sheet metal that generates a 3D deformation. To advance flexible manufacturing, Cai et al. [13] and Park et al. [14] developed a highly flexible forming technology that can efficiently produce 3D sheet metal sections with multiple curvatures. This process uses a forming tool consisting of an upper flexible roll and two lower flexible rolls in which the shape of the flexible roll can be changed vertically.

However, reconfigurable flexible forming systems still experience difficulties, such as problems related to positioning and locking pins and issues of uneven surface effects caused by small, discrete pins. This study proposes a new rolling machine design is to overcome the above-mentioned drawbacks of pin-type tooling. The rolling method utilised here differs from the previous methods. It produces variable wavy shapes in a single roller stand without the need for multiple rollers. The process is achieved by adjusting the rolls constructed from distinct disks with varying diameters and thicknesses. Different groupings and arrangements of these disks result in a variety of waveforms and dimensions.

2. Invented Multi-Disk Roller (MDR)

In the shape-forming process, two rollers are used to press a workpiece, deforming it until it reaches the desired shape and geometry that is machined onto the outer surface of both rollers. Figure 1 shows a schematic of a shape-rolling machine that produces corrugated plates characterised by amplitude and wavelength. A restriction of machined rollers (MRs) is that each roller set is dedicated to producing a specific shape and dimension, requiring a replacement in case of wear or failure. The proposed roller (upper and lower) suggests discretising the waveform by chopping the roller along its length into disks. In addition to other waveforms and dimensions that can be approximated using these disks, the required waveform can be obtained by synthesising these disks. Figure 2 shows the transformation from MR to MDR. The MDR overcomes the limitations of MR because of the manipulative susceptibility of disks and the recyclability of the configured disks. In the event of wear and failure, the disks can be reproduced by refining larger disks into smaller ones, allowing for continued use in operational processes.

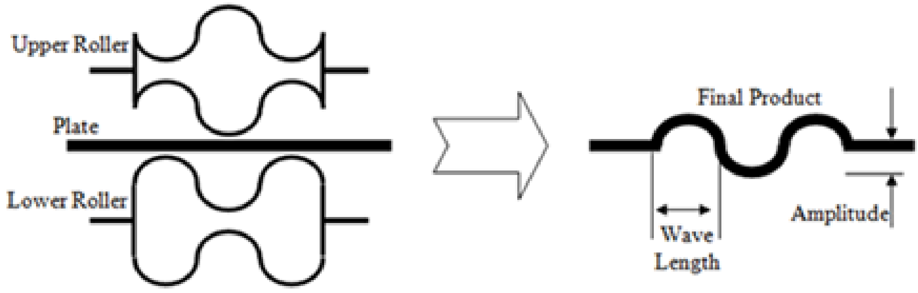


Fig. 1. Production of a corrugated plate characterised by amplitude and wavelength

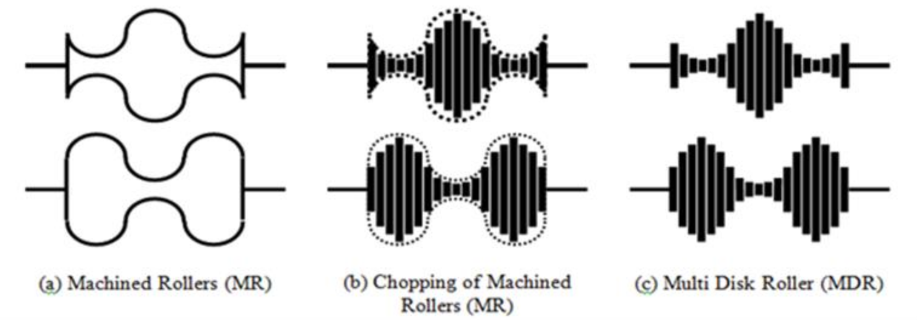


Fig. 2. Transformation from machined rollers (MRs) to Multi-disk rollers (MDRs)

3. Design of MDR

Roller disk dimensions (thickness and diameter) are crucial in the forming process. A thinner disk allows for better approximation of the waveform profile, but high-strength material is needed for disk manufacturing. Disk diameter also depends on thickness because they both determine the geometry the disk will generate. The rollers with multiple disks are multi-point forming tools whose geometric configuration is illustrated in Figure 3. Each disk has a uniform thickness of 1 mm, and the disk diameter is determined using a sine curve equation based on the roller's properties and dimensions. Referring to Figure 3,

$$H_f = R_U^n + t + R_L^n \quad \ldots(1)$$

$$R_U^n = \frac{H_f}{2} - y(x) - \frac{t}{2}\sin(\frac{2\pi nS}{L}) \quad \ldots(2)$$

$$R_L^n = \frac{H_f}{2} + y(x) - \frac{t}{2}\sin(\frac{2\pi nS}{L}) \quad \ldots(3)$$

Where L is the wavelength, n is the disk number, S is the disk thickness, t is the workpiece thickness (plate), x is the dimension along roller length, $y(x)$ is the deformed shape describing function and H_f is the distance between lower roller centre line and upper roller centre line. R_U^n and R_L^n are the upper and lower roller disk radii, respectively. A is the amplitude of the sine wave defined as follows:

$$y(x) = A\sin(\frac{2\pi nS}{L}) \,, \quad \text{where} \quad n = 1, 2, 3, \ldots$$

Solving these equations for (H_f = *120 mm, L = 40 mm, A = 10 mm, t = 0.5 mm, S=1 mm and n (1 to 40))* gives the results shown in Table 1. The disk arrangement on each roller is illustrated in Figure 4. The top roller starts ascending to configure the upper edge of the metal, and the lower roller starts descending to configure the lower edge of the metal.

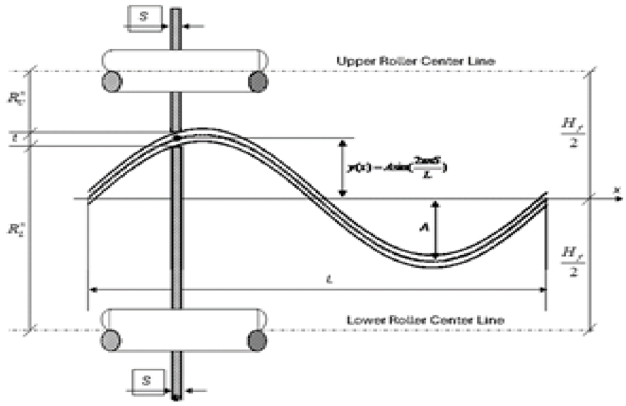


Fig. 3. Design of MDR

Table 1.
Calculated disk radii

Disk Number	Lower Roller (mm)	Upper Roller (mm)	Disk number	Lower Roller (mm)	Upper Roller (mm)
D1	58.19	61.31	D21	61.31	58.19
D2	56.66	62.84	D22	62.84	56.66
D3	55.21	64.29	D23	64.29	55.21
D4	53.87	65.63	D24	65.63	53.87
D5	52.68	66.82	D25	66.82	52.68
D6	51.66	67.84	D26	67.84	51.66
D7	50.84	68.66	D27	68.66	50.84
D8	50.24	69.26	D28	69.26	50.24
D9	49.87	69.63	D29	69.63	49.87
D10	49.75	69.75	D30	69.75	49.75
D11	49.87	69.63	D31	69.63	49.87
D12	50.24	69.26	D32	69.26	50.24
D13	50.84	68.66	D33	68.66	50.84
D14	51.66	67.84	D34	67.84	51.66
D15	52.68	66.82	D35	66.82	52.68
D16	53.87	65.63	D36	65.63	53.87
D17	55.21	64.29	D37	64.29	55.21
D18	56.66	62.84	D38	62.84	56.66
D19	58.19	61.31	D39	61.31	58.19
D20	59.75	59.75	D40	59.75	59.75

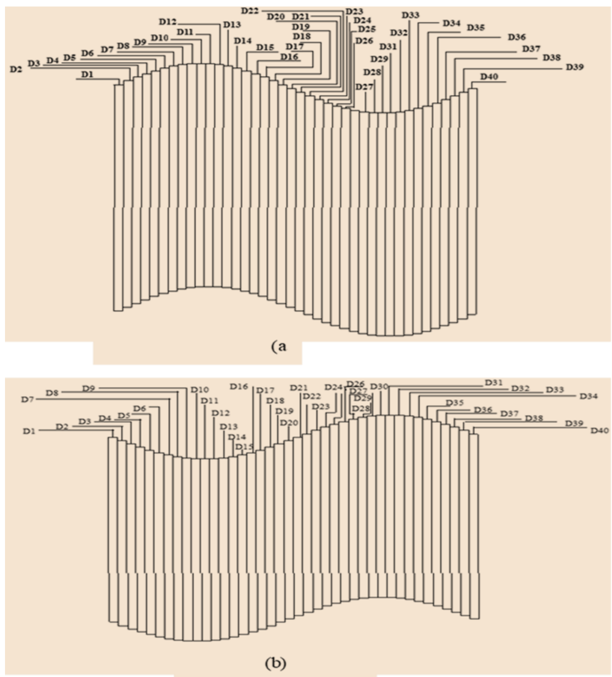


Fig. 4. Disk arrangement: (a) upper roller and (b) lower roller

4. General Configuration of MDR

The rollers synthesised from disks were arranged in a sequence, so they formed a sine wave curve with a specific dimension. Each roller has 240 disks, distributed over six waves, with each wave comprising 40 disks. One dimension of a sine curve is the wavelength which is calculated from the number of disks and their thicknesses. In this case, the wavelength of the reconfigured profile is L = 40 mm. Another dimension is the amplitude (A), the absolute value of the maximum displacement from a zero value during one oscillation period. The measurements involve diameters, so the amplitude can be determined as shown in Figure 5. *D10* represents the maximum disk radius, and *D30* represents the minimum disk radius.

Where $D10/2$ = 69.75 and $D30/2$ = 49.75

Amplitude = (($D10/2$) – ($D30/2$)) / 2 = 10.

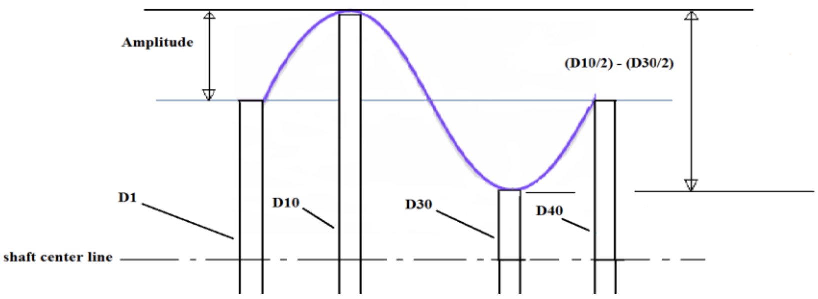


Fig. 5. Calculated sine curve amplitude

5. MDR Apparatus and Its Implementation

St35 steel alloy was selected for the disks because of its cost-effectiveness and suitability for plasma cutting processing that offers high cutting precision and quality edge cutting essential for achieving the desired shape. All cutting edges underwent grinding to produce a smooth contact surface which touches one another during disk assembly. The disks were then tightly secured along a shaft with a length of 530 mm and a diameter or 25 mm to prevent movement or separation during the forming process, as shown in Figure 6. The shaft holds a pillow block bearing that is composed of mounted units and is designed to provide shaft support with the mounting surface parallel to the shaft axis. The bolt holes in the bearing are usually slotted for adjustment during mounting.

The frame of the developed machine body is shown in Figure 7a. It consists of a ground base with two guide plates mounted on each side. Two upper mounting frames, as shown in Figure 7b, are attached to the top portion of the machine body with a top adjustment bolt. These frames are designed to provide vertical adjustment for the upper roller and carry and support the bearing guide. Each bearing guide is attached to the frame by bolts and nuts through aligned holes. The lower mounting frame system is similar to the upper one, except that the coupling nut is replaced by a bolt. A mechanism is used to set the height of the upper roller and adjust the distance between the two rollers, thereby controlling the passage of the metal during the forming process, as shown in Figure 8. A set screw is used to hold the bearing by forcing it through the bolt hole of the bearing, which is attached to the hand wheel to turn its movement. A lock nut is used to secure the screw onto the bearing, preventing it from loosening. In addition, a flat washer is placed beneath the bolt hole to provide a smooth rotation of the screw. The system used to control the pressure applied by the upper roller consists of a hex head bolt to move up and down through a coupling nut, providing a screw path. This mechanism converts rotational movement into linear movement, applying a torque to the roller. As the shaft bolt is rotated relative to the stationary threads (coupling nut), the bolt travels along its axis relative to the surrounding medium.

An electric motor gearbox system (1/2 HP with a speed of 50 rpm) with a gear train was used to transmit rotary motion. The gear train consists of spur gears to transmit power from one shaft to another (one gear on each shaft). The nature of the gear train depends on the relative position of the axes of the shafts (two roller shafts and input drive shaft) on which the gears are mounted. Each gear is mounted on a keyed shaft with a round bore and a set screw, ensuring that the gears are fixed relative to each other. The outside diameter of the roller's gears is 120 mm with 40 teeth, and the outside diameter of the gearbox is 60 mm with 20 teeth, reducing speed and increasing load capacity. The complete machine frame with rollers and its drive system is shown in Figure 9.

Straightening guides were used as an accessory tool and mounted on the machine frame, as shown in Figure 10. The guide consists of a right-angle, two-piece part mounted on a strip with a bolt and nut to allow for position adjustments to achieve the required spacing smoothly and easily.

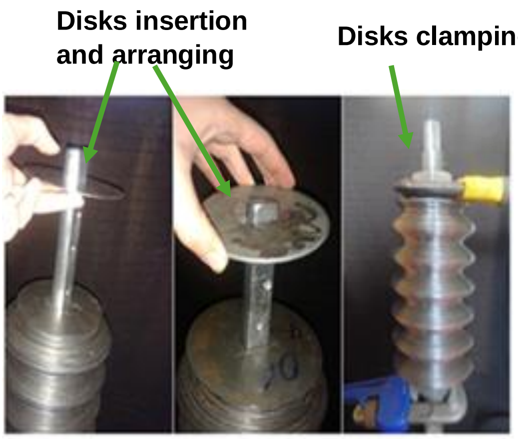


Fig. 6. Roller configuration process

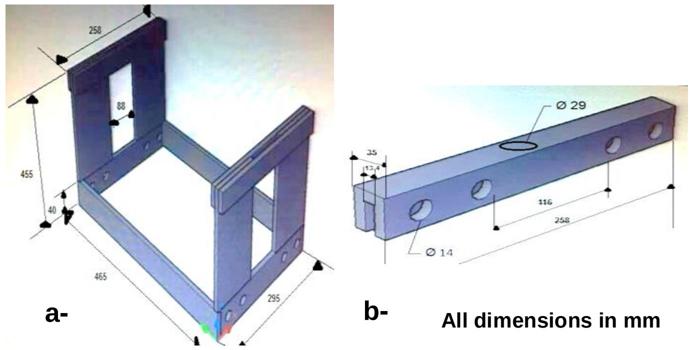


Fig. 7. (a) Machine frame, (b) Mounted frame

Fig. 8. Roller adjustment mechanism

Fig. 9. Full machine frame

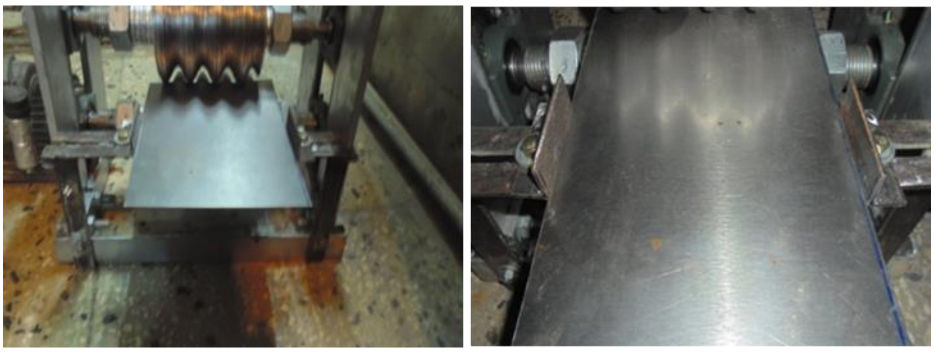
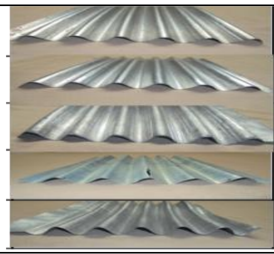


Fig. 10. Sheet guide and handle

6. Results and Discussion

The results obtained focus on the profiles produced, and they are discussed together with the design considerations in the roll-forming machine, the reconfigurable mechanism, the geometry of the rollers together with their effect on formed profiles and the benefits of using these rollers. Two different formed profiles are considered in this study: corrugated and multi-dimensional sine curved profiles. In both cases, the reconfiguration is achieved by rearranging the sequence of disks. Various materials with different thicknesses are used for the output-formed sheets, as indicated in Table 2. In all cases, the amplitude value is calculated using *D10* and *D30,* as explained earlier.

Table 2
Formed profiles, materials and their dimensions

Material type	Material thickness (mm)	Measured amplitude [A] (mm)	Measured wavelength [L] (mm)	Number of passes	Formed profile
Steel	0.5	9.9	40	44	
Steel	0.8	9.8	40	57	
Steel	1	9.86	40	25	
Lead	1	10.4	40	6	
Zinc	0.3	9.3	40	7	

6.1 Corrugated profiles

Corrugated profiles are obtained by changing the disk arrangement, which is accomplished by adding and subtracting disks, as detailed in Table 3, to match the die shape profile. Table 3 shows the different roller configurations, produced corrugation profiles, their die shape and measured dimensions. The disk arrangement used to produce these profiles is illustrated in Figure 11. The produced corrugated shapes include curves and straight lines. To form a straight line, a sequence of the same disk diameters is required; each disk repeated two times for each wave results in a maximum line length of 6 mm. However, this length is insufficient compared with a standard profile and does not produce a clear formed profile. This limits the number of repetitions, where the maximum wave number reached is only two waves.

The dimensional accuracy of the finished part is affected by the springback property of the shaped metal which in turn causes elastic recovery of deformed parts. As seen in Table 3, the measurements are greater than the die shape. The final form of a part is changed by springback, making it difficult to produce the desired part geometry. Controlling the springback in sheet metal forming is a crucial manufacturing problem. Unless the springback is accurately estimated in advance, a sheet of metal that has been accurately corrugated, shall readjust itself, preventing the proper shape of the corrugations from being retained. Springback can be eliminated by over-forming. The sheet metal is overformed to a smaller dimension than needed. The recovery of the material from springback results in a calculated increase in dimensions. This increase makes the recovered dimensions match the original design. Parameters such as material property, sheet thickness and tooling geometry affect the springback behaviour.

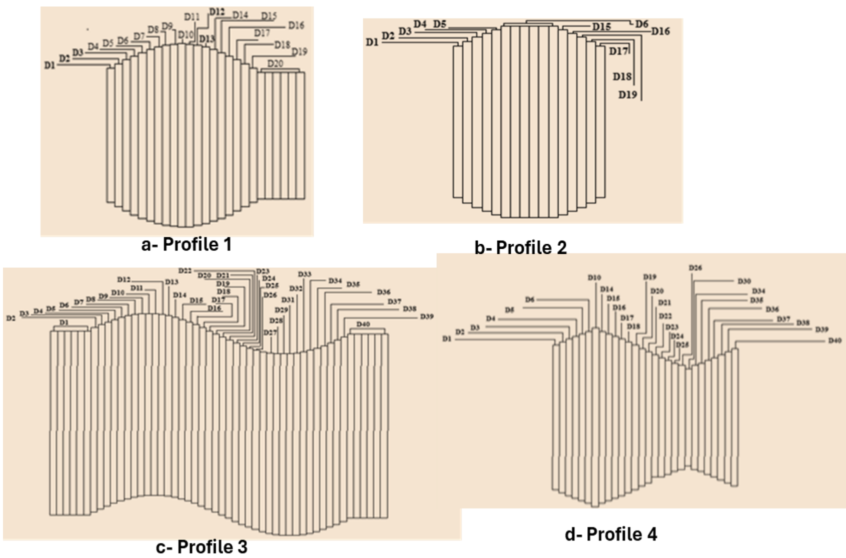
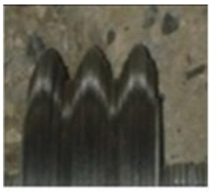
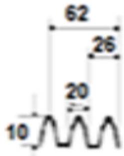
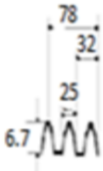
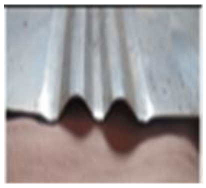
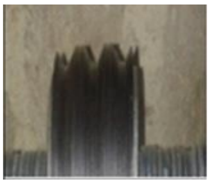
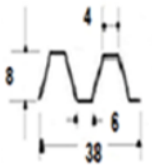
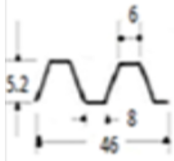
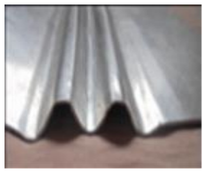
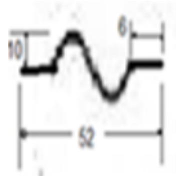
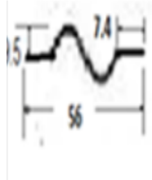
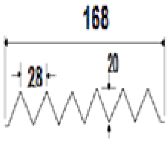
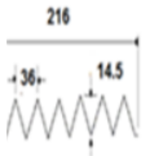


Fig. 11. Disk sequence of corrugated profiles

Table 3
Corrugated profiles and their dimensions

	Roller configuration	Top configuration of roller	Desired dimensions (mm)	Measured dimensions (mm)	Formed profile
1					
2					
3					
4					

Nevertheless, some shape defects, like edge waves, bending in the longitudinal and vertical planes, and twisting, can occur during the rolling process, as shown in Figure 12. To prevent these defects, the mechanisms that cause them should be examined. Shape orientation, which is the part’s position relative to the roll axis, is an important element of roll design. It affects part quality, causing shape defects and limiting the effectiveness of roll-forming passes, making it difficult to achieve the desired dimensional accuracy. Therefore, accessory tooling is necessary to mount the part on horizontal axes between driven roll stages. When the length sheet is fed through a roll-forming machine, a guiding device is used to ensure the part’s sides are properly aligned as it progresses from pass to pass. This tooling process eliminates defects.

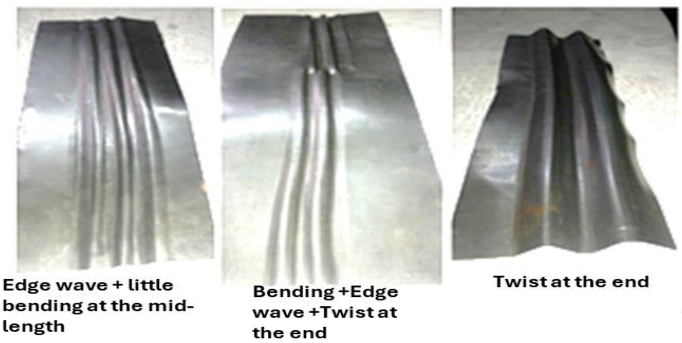


Fig. 12. Defects of rolled profiles

6.2 Multi-dimensional sine wave curve profiles

Multi-dimensional sine wave curve profiles are divided into the wavelength curve changes (amplitude) and the length curve changes (wavelength).

6.2.1 Multi-wavelength sine wave curve profiles

In this type, the wavelength is changed whilst maintaining the same value of the amplitude (10 mm), with disks 10 and 30 remaining unchanged. This process requires reducing the number of disks used to get the specific dimensions. Sine wave curve is symmetrical to the upper and lower parts of the waveform, and each half is symmetrical so that the amount of any disk reduction must be the same for each quarter. In other words, the amount of reduction is multiplied by four. Table 3 shows the derived wavelength which is expressed as follows:

$L_{new} = L_{reference}$ – (The amount of disks reduced from one quarter*4) …(4)

Where $L_{reference}$ defines the wave’s full length that includes 40 disks.

Fine wavelength can be produced as disk reduction increases. The smaller the set of disks, the finer the curve, so more disks are needed to make a smooth surface profile. The maximum number of disks reduction that can be obtained is five disks. Tables 4 and 5 show the dimensions of profiles produced and disks removed to obtain the specific dimensions for sheet thicknesses of 0.5 mm and 0.8 mm, respectively.

Table 4.
Multi-sine wave curve profiles and their dimensions for sheet thickness of 0.5 mm

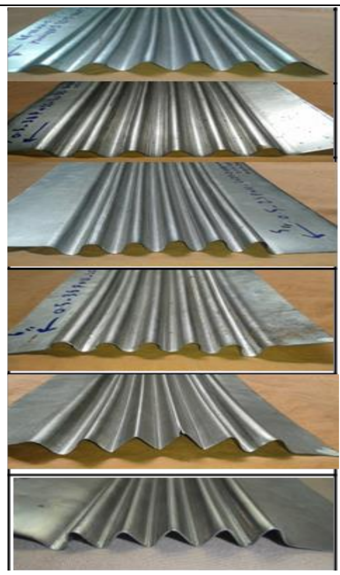
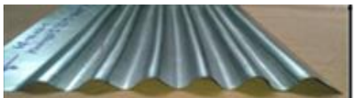
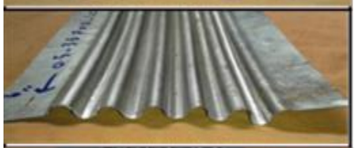
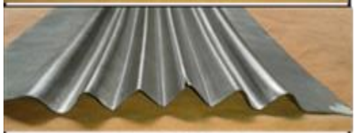
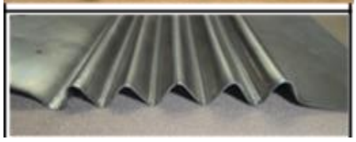
Wavelength [L] (mm)	Amplitude [A] (mm)	Number of passes	Disk removed	Formed profile
36	8.5	30	D2-D19-D22-D39	
32	7	38	D2-D3-D18-D19-D22-D23-D38-D39	
28	5.7	25	D2-D3-D4-D17-D18-D19-D22-D23-D24-D37-D38-D39	
24	6	36	D2-D3-D4-D5-D16-D17-D18-D19-D22-D23-D24-D25-D36-D37-D38-D39	
24	6.16	48	D3-D5-D7-D9-D11-D13-D15-D17-D23-D25-D27-D29-D31-D33-D35-D37	
20	5.76	43	D1-D3-D5-D7-D9-D11-D13-D15-D17-D19-D21-D23-D25-D27-D29-D31-D33-D35-D37-D39	

Table 5.
Multi-sine wave curve profiles and dimensions for sheet thickness of 0.8 mm

Wavelength [L] (mm)	Amplitude [A] (mm)	Number of passes	Disk removed	Formed profile
36	8	35	D2-D19-D22-D39	
32	6.8	45	D2-D3-D18-D19-D22-D23-D38-D39	
28	6.1	35	D2-D3-D4-D17-D18-D19-D22-D23-D24-D37-D38-D39	
24	6.7	54	D2-D3-D4-D5-D16-D17-D18-D19-D22-D23-D24-D25-D36-D37-D38-D39	
24	5.59	56	D3-D5-D7-D9-D11-D13-D15-D17-D23-D25-D27-D29-D31-D33-D35-D37	
20	6.15	48	D1-D3-D5-D7-D9-D11-D13-D15-D17-D19-D21-D23-D25-D27-D29-D31-D33-D35-D37-D39	

6.2.2 Multi-amplitude sine wave curve profiles

In this group, the wavelength is fixed whilst the amplitude is changed by removing disks in the peaks and compensating with a certain number of disks to maintain wavelength. Tables 6 and 7 list the profiles produced with the disk arrangement for two different sheet metal thicknesses. Figure 13 shows the roller configurations for each profile of changed amplitude. The number of waves is reduced because the compensated disks are taken from the other waves to maintain the same wavelength.

Disks are set to clamp at their ends with a heavy hex nut used with a threaded insert which is fixed with a dimple drilled into the shaft. The set of disks is 240 mm in length. The reduction of disks to form the required configuration changes the position of the clamped nut; therefore, washers are used to compensate the removed disks to maintain these clamps at their positions for all formed profiles, as seen in Figure 14.

In this group, the produced profiles are free of any shape defects, unlike the corrugated profiles. This improvement is attributed to the sheet metal guide discussed earlier. The formed profiles include changes in amplitude and wavelength. The wavelength dimension of all produced profiles is identical with the die-shape wavelength values, but the amplitude dimension is not identical within the die-shape amplitude. The amplitude of the profile is measured by the gap distance available between rollers. Two techniques are followed to remove disks. To reach the die shape wavelength, the disks are removed in ascending direction, maintaining disks (1, 20, 21 and 40) at their position. These disks are considered the start and end points of the curve, and the disks between them are removed sequentially. This configuration is applied to wavelengths ranging (36–24) mm. Figure 15 shows the roller configuration results from this technique, and Figure 14 shows the clearance generated between rollers.

The other wavelength values take the same shape but with varied sizes according to the part length. The clearance configuration between rollers shown in Figure 16 is the same for all formed profiles. As the number of removed disks increases, the difference between the diameters of the remaining disks grows, leading to a greater number of passes over a considerable area. This technique results in a high compressional stress on the edges of the disks, causing them to fold. Therefore, another technique is applied to the wavelength (24). Disks (1-20-21-40) remain at their position where the even-numbered disks are removed, and the sequence of disks remains in the roller (e.g. D1-D3-D5-D7-D9-D11-D13-D15-D17-D19…). This arrangement is applied to wavelengths 24 and 20. For the 20 mm wavelength, the number of disks that should be removed is 20 disks. Following this technique, the disks removed were 10 and 30 to minimise the difference between the disks. Therefore, the die shape amplitude is calculated as the difference between disk 9 (which is the same diameter as disk 11) and disk 29 (which is the same diameter as disk 31). This configuration mechanism produced some shape defects, as shown in Table 8. High concentrations of stresses and strain are developed at sharp peaks caused by disk reduction. Reduction of the peak area makes it weaker, and the material starts cracking. Fracturing starts at these sharp peaks, and the reduction in the roller disk makes it brittle, and the plastic deformation in the sheet to exceeds the ductility of the metal, leading to rupture and tearing of the sheet metal. As seen in Table 8, necking develops after some strain, causing thinning and stretching. As previously mentioned, deformation becomes concentrated in the peak area, and the necking further intensifies the deformation, causing the part to stretch and eventually fracture. The capability of the machine to handle the amplitude of the profile is restricted by certain design attributes, such as the roller gap control. A key target of roll

Table 6.
Formed profiles of 0.5 mm sheet thickness and their dimensions

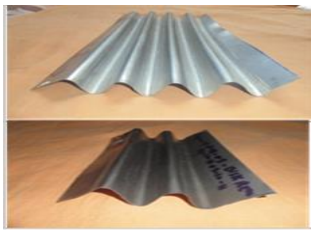
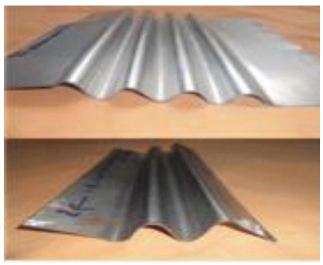
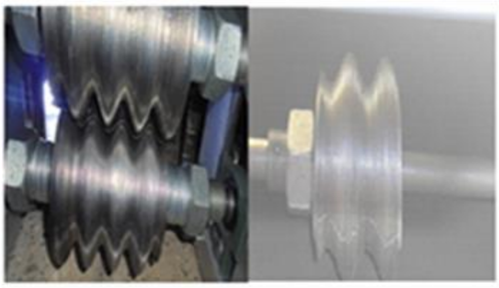
Die shape amplitude	Measured amplitude	Number of waves	Compensated disks	Number of compensated disks	Formed profile
9.88	9.3	4	D9-D11-D29-D31	One for each peak	
8.91	10.25	2	D8-D12-D28-D32	Three for each peak	

Table 7.
Formed profiles of 0.8mm sheet thickness and their dimensions

Die shape amplitude	Measured amplitude	Number of waves	Compensated disks	Number of compensated disks	Formed profile
9.88	9.3	4	D9-D11-D29-D31	One for each peak	
8.91	9.6	2	D8-D12-D28-D32	Three for each peak	



a b

Fig. 13. Roller configuration of reconfigured amplitude of sine wave curve for A = 9.88 (a) and A = 8.91 (b)

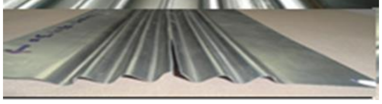
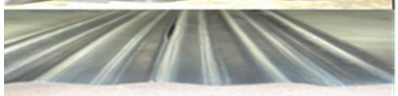
Fig. 14. Clamped configuration

Fig. 15. Roller configuration

Fig 16. Gap between rollers

pass design is to accurately build a sequence of reductions to minimise the relative differences in shape changes between different areas, thereby avoiding material imperfections. Improper reductions of the product can cause warping or cracking of the material, as presented in the profile. Another technique for forming the part is adopted in the next section.

Table 8.
Shape defects of formed profiles

Wavelength of profile	Profile thickness of 0.8 mm	Profile thickness of 0.5 mm
24		
20		

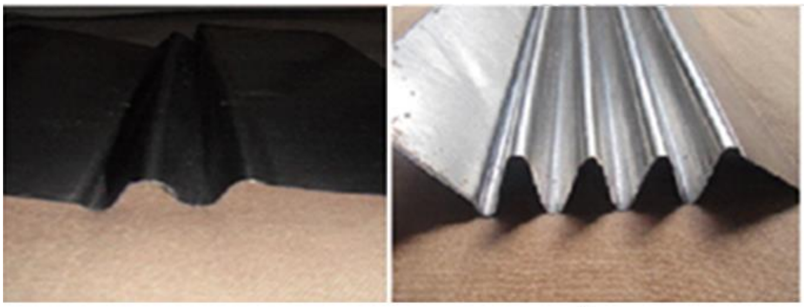
6.3 Variable wave number per pass

A sequential forming process is used to produce accurate dimensional parts without serious defects. The formed part is constructed firstly by partitioning the die with only two waves, followed by the cumulative addition of other waves. For steel-type material, the number of passes required for the production of a two-wave formed sheet is 15 and 22 for four waves, which ensures the efficiency of this procedure. The formed part closely matches the die shape's wavelength and achieves an amplitude value that is reasonably close to the desired value. The work hardening and strength of the formed part are effective parameters that facilitate the production of the wave part without failure. The produced profile is shown in Figure 17, and its dimensions are shown in Table 9.

For lead-type material, the forming process using the same roller configuration is slightly more complicated. Only two waves are formed because of the penetrating lines formed on the metal surface which substantially increase the wavelength and make pulling the metal difficult and impossible. Figure 18 shows the formed part of a two-wave profile and penetrating lines on the surface.

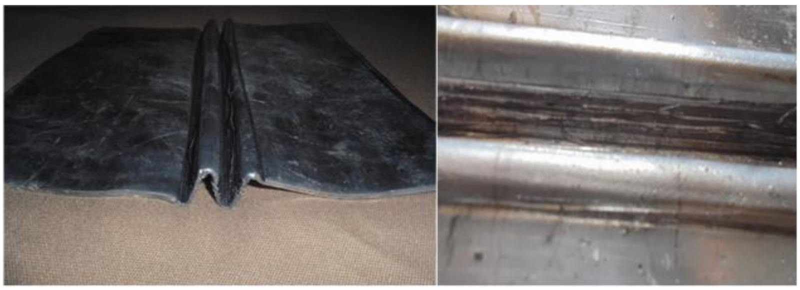
Table 9.
Dimensions of formed profiles

Material type	Material thickness (mm)	Die shape amplitude (mm)	Die shape wavelength (mm)	Measured amplitude (mm)	Measured wavelength (mm)	Number of passes
Steel	0.5	9.88	20	9.25 (for two cycles) 8.4 (for four cycles)	20	15 (for two cycles) 22 (for four cycles)
Lead	3	9.88	20	8.325 (for only two cycles)	20	25



a- b-

Fig. 17. First stage of the formed profile consisting of two waves (a) and second stage of the formed profile consisting of four waves (b)



a- b-

Fig. 18. Formed lead sheet (a) and penetrating lines on surface (b)

7. Conclusions

This research aims to improve the flexibility in roll forming process and reconfigurability of the related manufacturing tools. It focuses on the novel idea of using multiple thin disks with varying diameters to compose the upper and lower rollers of the rolling/roll forming process which then converge the shape of the target sheet profile. This interesting approach of MDRs positively affects the reparation effort of the rollers in case of wear or failure. The reason is that only the replacement of single disks is necessary, thus avoiding the full reproduction of the rollers. Additionally, defective disks can be recycled by machining bigger disks into smaller ones which leads to cost savings. MDRs can produce a diverse range of parts, including sine wave curves and corrugated profiles, especially with acute requirements on geometry modification. The MDR can produce 13 different parts on the same machine. The reconfigurable designs include the part scale and shape. The primary design limitation in achieving a greater variety of outputs is the number of disks used which determines the shape and dimensions of the product. This limitation can be overcome by increasing the size of the roller and using a greater number of disks, enabling the production of multiple profile geometries. The discrete nature of the designed rollers allows for reconfiguration into multiple configurations, saving cost and time necessary to invent new tools. Various products with different geometries and dimensions have been manufactured, confirming the tool's capability. Inadequate reductions in both the manufactured part and the metal guide, along with alignment issues, bring out defects such as dimensional irregularities and fractures. This study has identified solutions to avoid these defects.

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تصميم وتنفيذ ماكنة لف متعددة التكوين

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المستخلص

لعقود من الزمان، كانت الصفائح المتموجة المعدنية تُصنع غالبا باستخدام آلات تشكيل تقليدية تتضمن استخدام كل من الأسطوانات السفلية والعلوية أو قالب وضاغط كعناصر رئيسة للتشكيل. من الناحية الاقتصادية، فأن استخدام مثل هذه الآلات مع العمليات المتصلة بها يوجد لها عيوب، إذ يتم اضافة نفقات إضافية لتحسين أدوات التشكيل وادارتها . وللتغلب على مثل هذه العيوب، تم استخدام آلات قابلة للتشكيل (أنظمة التصنيع المخصصة وأنظمة التصنيع المرنة) كفئة أخرى من الآلات التي تتمتع بمرونة عالية في إنجاز عمليات التشكيل. يتم بناء الآلات القابلة للتشكيل ببساطة حول عائلة معينة من الأجزاء المُنتجة وتسمح بمرونة عالية في نظامها. ونتيجة للتطورات الأخيرة في مجال تصميم الآلات القابلة للتشكيل ، فان الورقة البحثية الحالية تقترح تصميماً جديداً لتشكيل الصفائح المعدنية يسمى الأسطوانة المتعددة الأقراص ال Discrete Multi Disk Roller (MDR) كبديل للتصميم الحالي للأقراص. على عكس العمليات الحالية، يمكن لـ MDR تقليل التكاليف الإنتاجية الجماعية الناجمة عن فقد المواد وتقليل الأخطاء في التشكيل بفعالية. فضلا عن ذلك، يتضمن التصميم المقترح استخدام أقراص متعددة كأقراص قابلة للتشكيل. تم وصف تقنية وإجراءات MDR وتشكيل صفائح مموجة بأبعاد وأشكال مختلفة للتحقق من قابلية استخدام الاقراص القابلة للتشكيل وهي عنصر حرج في هذه العملية التشكيلية. تم إنتاج ثلاثة عشر جزءًا بتكوينات مختلفة باستخدام ماكنة ال MDR.
