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Design and Fabrication of a Three - Rolls Plate Bending Machine

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Abstract
This paper is aimed at designing and fabricating a low cost motorized 3-rolls plate bending machine to bend a metal plate up to 6 mm thick mild steel plates. The major components of the machine design for are: the rolls shaft diameters; thee chain drive; the spur gears drive and holding keys and the framework. Materials were selected to meet the machine requirements of strength, machine accuracy and reliability. The machine components were constructed by the various machining processes of cutting, turning and milling, and were thereafter arranged and joined together by appropriate joining methods such as welding and screw joints. The fabricated motorized 3-rolls plate bending machine with a 10hp electric motor is quite effective and efficient with maximum thickness of 6mm mild steel plate. The total cost of production is $1,363.64 which is relatively cheap compared to equivalent available in the market.
Keywords: Bending parameters, chain drive, keys, roll-bending, roll- shaft, spur gears drive.
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I. Introduction

In metalworking, rolling is a metal forming process in which a metal plate is passed through a pair or more rolls. Rolling is a complex process which is determined by the properties of the material being rolled; its thickness being a major factor. The parameters used in designing and fabricating the 3-rolls plate bending machine depends on these properties and the corresponding thickness of the material in use. In this process, the diameter of the metal plate or sheet being rolled does not change after the rolling. That is to say, that the initial and final thickness will be equal. The presence of cracks is also avoided during the course of the process. This was shown in the plastic and elastic deformation process in later stages (Boljanovic, 2004).

For the plastic deformation, the plate is expected to be able to retain its thickness after roll bending. Considering the magnitude of stresses that exist during the roll bending process of steel, as well as non-reduction in the thickness of the material, the roll bending process can be analyzed in two ways:

i. Bending in the centrally located inner zone, on both sides of the neutral zone, is a domain of elastic-plastic deformation, while
ii. Bending in the outlying zones (on both the inside and outside of the bend), is a domain of pure plastic deformation.

Bending in the actual sense, is a domain of elastic-plastic deformation and can be considered as a linear stress problem (Carden et al., 2002).

In the rolling process, the radius through which the sheet steel is bent must be smaller than the required radius because of the spring back formation (Ahmed et al., 2012). They also show that the amount of spring back depends on several materials and such machine properties as the elasticity modulus, shape of the stress-strain curve, sheet thickness, roller dimensions, and so on. To study the spring back phenomenon produced on steel sheets, the rolling process is often used.

Yang and Shima (1988) discussed the distribution of curvature and calculated bending moment in accordance with the displacement and rotation of rolls by simulating the deformation of a workpiece with a U-shaped cross-section in a three-roller bending process.

Kim et al (2007) proposed a formulation to determine the bending force on rollers, the driving torque, and the power in the three-roll bending of a thin plate.

Analytical solutions of bending process have been presented by several researchers (Kim et al., 2007; Dongjuan et al., 2007; Wagoner and Li, 2007); however, for inverse analysis of springback in free bending process, a state of plain strain and negligible shear deformation is assumed (Behrouzi et al., 2008).

Asghari et al (2008), determined the force and power required to drive the three-roller plate bending machine, when it is unloaded with a workpiece and when it is load to roll a maximum of 5mm steel plate.

Adsul et al (2013) stated that the factors that should be considered while calculating bending force are material properties, width, thickness, number of passes, bending radius, force developing mechanism and link.

The aim of this study is to design and fabricate a motorized 3- rolls plate bending machine to bend a metal plate up to 6mm in thickness and 1200mm in width into cylindrical forms.

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2. Methodology

2.1 Design considerations

For the machine to be reliable and accurate in its performance, there are so many factors to be considered. Some of the important design considerations are: properties of the metal plate to be rolled; size of the shaft (in diameter and length); the force, torque and power required to roll a given thickness and maximum reliable thickness.

2.2 Design of machine elements

2.2.1 Design of Roll Shaft Diameter

The force on acting on the sheet metal plate when the weight of the shaft is neglected and the shaft diameter were computed as 4064.6N and 94.3mm, respectively using eqns. (1) and (2) given as (Olunlade et al., 2018):

$$F = \frac{4 \times E \times I \times Sf}{R \times L_{sh}} \tag{1}$$

$$T_e = \sqrt{M_{s^2} + T_{s^2}} = \sqrt{6909820^2 + 2032.3d_s^2} = \frac{\pi}{16}\tau_{as}.d_s^3 \tag{2}$$

Where,
E = modulus of elasticity of the sheet metal plate = 210 x 10^3 N/mm^2
R= radius of curvature = (d_{max} + t)/2 = 1203mm
d_{max} = maximum diameters of sheet metal to be rolled = 2400mm
t= maximum thickness of sheet metals to be rolled = 6mm
I = moment of inertia of sheet metal plate =wh^3/12 = 21, 945.6mm^4
w = width of mild steel sheet = 1219.2mm
h = thickness of mild steel sheet to be rolled = 6mm
Sf = factor of safety = 2.
L_{sh} = length of rolling shaft = 1700mm
M_s = banding moment = F.L_{sh} = 6909820Nmm
T_s = Fd_s/2 = 2032d_s Nmm
d_s = roll shaft diameter (to be determined)
τ_{as}= allowable stress of the shaft interval = 42N/mm^2.
And resolving the eqn. (4) Using standardized polynomial function and inserting values, the shaft diameter was computed as, d_s = 94.3mm. We use d_s = 100mm

2.2.2 Design of Drive Electric Motor Power

The bending moment of the cylindrical section M_{cs}, the bend angle θ, the supporting force F_2 on the roll plate and the pressure force F_1 generated by the upper roller (shown in Figure 1), the deformation torque T_d, the friction torque T_f , the roller drive torque T_{rd} on the lower roller as well as the lower roller drive power P were computed as 3.38KNm, 20.69°, 95.7KN, 179.1KN, 1.69KNm, 3.89KNm, 5.58KNm and 9.92 Hp, respectively from eqns. (3 - 10) given as (Boljanovic, 2004; www.machinemfg.com/08-02-2019):

$$M_{cs} = k_r.YS.\frac{w.t^2}{4} \tag{3}$$

$$\theta = \sin^{-1}\left(\frac{\alpha}{d_{min} + d_2}\right) \tag{4}$$

$$F_2 = \frac{2M_{cs}}{d_{min}\ \sin\theta} \tag{5}$$

$$F_1 = 2\ F_2\cos\theta \tag{6}$$

$$T_d = \frac{M_{cs}d_2}{d_{min}} \tag{7}$$

$$T_f = f(F_1 + 2F_2) + \mu\left(F_1\frac{D_1}{2}\frac{d_1}{d_2} + F_2D_2\right) \tag{8}$$

$$T_{rd} = T_d + T_f \tag{9}$$

$$P = \frac{2\pi\ T_{rd}n}{60\eta} \tag{10}$$

Where,

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w = maximum with of sheet place = 102192m
t = thickness of rolled stall sheet = 0.006m
YS = material Yield limit = $280x10^3$ KN/m^3
k_r = reinforcement coefficient = 1.1
α = lower roller centre distance = $d_s + t$ = 0.106m
$d_1 = d_2 = d_s$ = lower roller diameter = 0.10m
d_{min} = minimum diameter of plate to be rolled = $2d_1$ = 0.20m
d_2 =lower roller diameter = 0.10m
f = coefficient of rolling friction = 0.008
μ = coefficient of sliding friction = 0.01
D_1, D_2 = upper roller and lower roller diameter neck = 0.05m
n = lower roller rotational speed = 10 rpm
η = transmission efficiency = 0.79.

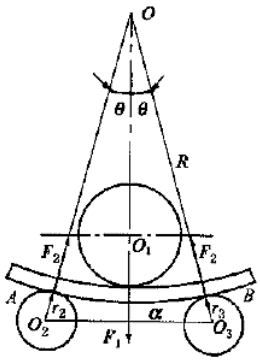

Figure 1: Force analysis of roll bending (www.machinemfg.com/08-02-2019)

2.2.3 Bending Parameters

The minimum bend radius, the maximum bend radius, the bend radius, bend allowance and the springback effect were computed as 0.018m, 2.035m, 1.20m, 0.434m and 0.21mm respectively from eqns. (11 – 15) given as (Boljanovic, 2004):

$$R_{i,min} = c.t \quad (11)$$

$$R_{i,max} = \frac{t.E_s}{2YS} \quad (12)$$

$$R_1 = \frac{d_{max}}{2} \quad (13)$$

$$L_n = \frac{\pi\ \theta^0}{180^0}\sqrt{R_0 R_i} \quad (14)$$

$$AR = \left(R_{1,min} + \frac{I}{2}\right)(1 - K_s) \quad (15)$$

Where,
c = variety of materials = 3
t = thickness of sheet mate plate = 0.06m
E_s = modulus of elasticity of sheet plate material = $190x10^6$ KN/m^2
YS = yield stress of sheet plate material = $280x10^3$ KN/m^2
d_{max} = diameter of roll sheet plate = 2.40m
θ = bend angle = 20.69^0;
R_0 = outer bend radius = 1.206m
R_i = inner bend radius = 1.20m.
$R_{i,min}$ = Minimum bend radius = 18min
K_s = Sheet metal plate factor = 0.99 (R_f/t = 3 for plain carbon steel plate).

2.2.4 Design of Chain Drive

The chain drive design power, the member of teeth in the drive and driven sprockets, the triplex roller chain pitch, the chain speed, the torque transmitted by chain drive, the total pull on the chain drive, the bearing pressure of the chain drive, the permissible bearing pressure, the working factor of safety, the actual chain length, the pitch circle

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diameters of the chain drive, the outer diameters of the smaller and larger sprockets were computed were computed as 11.19kw, 17 and 34, 38.1mm, 0.30m/s, 2544.21Nm, 24,930.3N, 1510.9N/cm^2, 1820.3 N/cm^2; 17.05, 69.78 links (2667mm), 207.3mm and 412.9mm , 227.6mm and 433.2mm, respectively from eqns. (16 - 28) given as (Iwis, 2010; Khurmi and Gupta, 2012):

$$P_{des} = k_c \times P_m \tag{16}$$

$$Z_{c2} = \frac{n_{c1}}{n_{c2}}.Z_{c1} \tag{17}$$

$$V_c = \frac{Z_{c1} \times n_{c1} \times p}{60,000} \tag{18}$$

$$M_c = \frac{9550 \times P_m}{n_{c1}} \tag{19}$$

$$p_T = p_t + p_c + p_s \tag{20}$$

$$P_r = \frac{P_T}{A_r} \tag{21}$$

$$P_P = \frac{P_v.\lambda}{f_1.f_2} \tag{22}$$

$$\text{Working factor of safety} = \frac{\text{breaking load}}{\text{design load}} \geq 7.0 \tag{23}$$

$$L_c = 2a_p + \frac{Z_{c1} + Z_{c2}}{2} + \frac{(Z_{c2} - Z_{c1})}{39.5a_p} \tag{24}$$

$$d_1 = \frac{p}{\sin\left(\frac{180^0}{Z_{c1}}\right)} \tag{25}$$

$$d_2 = \frac{p}{\sin\left(\frac{180^0}{Z_{c2}}\right)} \tag{26}$$

$$d_{01} = d_1 + 0.8d_o \tag{27}$$

$$d_{02} = d_2 + 0.8d_o \tag{28}$$

Where,
K_c = load concentration factor = $k_1 \times k_2 \times k_3$
k_1 = heavy shape coefficient = 1.4
k_2 = fabrication coefficient = 0
k_3 = tooth factor = 1.25
P_m = motor power = 10hp = 7.46kW.
Z_{c1} = number of teeth in the driver sprocket (taking as min teeth) = 17
Z_{c2} = number of teeth in the driven sprocket = 34.
n_{c1} = motor speed = 28 rpm
n_{c2} = driven shaft speed = 14pm
P_t = 24, 866.7N
P_c = 1.8N
P_s = 61.8N
P_T = total pull on drain = 24, 930.3N
A_r = bearing are = 16.50cm^2
P_v = bearing pressure for corresponding teeth = 2912.5 N/cm^2
λ = friction travel = 0.63
f_l = effect of lubrication = 1.0

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f_2 = for drive comprising two shafts = 100cm
Breaking load = 425000N
Design load = total pull on drain = 24, 930.3N
a_p = Centre distance, C / pitch, p = 1000 / 38.1 = 26.25mm
p = chain pitch = 38.1 mm
d_1 = outer diameters of the smaller sprocket = 207.3mm
d_2 = outer diameters of the larger sprocket = 412.9mm
d_o = roller diameter = 25.4mm

2.2.5 Design of spur gear drive

The transmission ratio of the spur gear, the minimum number of teeth on the pinion to avoid interference, the gear life in number of cycles, the initial design torque, the equivalent young modulus of elasticity of the pinion and wheel, the design bending stress on gears teeth rotating in both directions, the design compressive (contact) stress on gears teeth, the minimum centre distance between the pinion and wheel, the number of teeth in the pinion and wheel of the gear drive, the module of the gear, the revised centre distance, the revised design torque of pinion, the bending strength of gear, the wear strength were computed as 1.4, 14, 0.84 x 10^7 cycles, 6614.93Nm, 206 x 10^3N/mm^2, 361. 84MPa, 1364.07MPa, 230mm, 20 and 28 teeth, 240mm, 72mm, 200mm and 280mm, 0.15m/s, 0.36, 5603223.51Nmm, 196.78MP$_a$, 1232.33MPa, respectively from eqns. (29 – 47) given as (Chand et al., 2012):

$$i = \frac{n_{g1}}{n_{g2}} \tag{29}$$

$$z_{min} = \frac{2A_w}{i\left[\sqrt{1+\frac{1}{i}\left(\frac{1}{i}+2\right)\sin^2\varphi} - 1\right]} \tag{30}$$

$$g_1 = 60 \times x_1 \times x_2 \times x_3 \times x_4 \times n_{g1} \tag{31}$$

$$[M_t] = k_g . M_t \tag{32}$$

$$E_{eq} = \frac{2E_{g1} \times E_{g2}}{E_{g1} + E_{g2}} \tag{33}$$

$$[\sigma_b] = \frac{\sigma_e}{k_e fos} \tag{34}$$

$$[\sigma_c] = C_R \times H_{RC} \times K_{cl} \tag{35}$$

$$a \geq (i+1)\sqrt[3]{\left(\frac{0.74}{[\sigma_c]}\right) \times \frac{E_{eq} \times [M_t]}{i \times \psi}} \tag{36}$$

$$Z_{g2} = i \times Z_{g1} \tag{37}$$

$$m = \frac{2 \times a}{Z_{g1} + Z_{g2}} \tag{38}$$

$$a_r = \frac{m(Z_{g1} + Z_{g2})}{2} \tag{39}$$

$$b = \psi \text{ x } a \tag{40}$$

$$d_{g1} = m \times Z_{g1} \tag{41}$$

$$d_{g2} = m \times Z_{g2} \tag{42}$$

$$V_g = \frac{\pi \times d_{g1} \times n_{g1}}{60} \tag{43}$$

$$\psi_p = \frac{b}{d_{g1}} \tag{44}$$

$$[M_t]_r = M_t . k_c k_d \tag{45}$$

$$\sigma_b = \frac{(i+1) \times [M_t]_r}{a \times m \times b \times y} \tag{46}$$

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$$\sigma_c = 0.74 \times \left(\frac{i+1}{a}\right)\sqrt{\left(\frac{i+1}{i \times b}\right) \times E_{eq} \times [M_t]_r} \qquad (47)$$

Where,
n_{g1} = speed of pinion gear = 14rpm
n_{g2} = speed of wheel = 10rpm
A_w = fraction by which standard addendum for the wheel should be multiplied = 1
i = transmission ratio = 1.4
φ = pressure angle = 20º
x_1 = number of runs per day = 8hours
x_2 = number of days runs per week = 6days
x_3 = number of weeks runs per gear= 52weeks
x_4 = number of years runs = 14rpm
K_g = Design load factor = 1.3
M_t = transmitted power = 7.460kW
$E_{g1} = E_{g2}$ = Young's modulus of electricity of pinion and wheel = 206 x10^3N/mm^2
σ_e = Fatigue strength = $1/2\sigma_u$ = 825MPa
σ_u = ultimate stress of AISI 4340 steel
K_e = Fatigue strength reduction factor = 1.2
fos = factor of safety = 1.9
C_R = 26.5; H_{RC} = 50; for HB $\geq$ 350
N = 0.84x10^7 < 25x10^7 cycles

$$K_{cl} = 6\sqrt{\frac{10^7}{N}} = 1.03$$

ψ = initial gear form = 0.30.
K_c = load concentration factor = 1.01
K_d = dynamic load factor = 1.1
y = form factor = 0.384.

2.2.6 Design of keys for pinion/wheel

The diameter of the round key to secure the pinion and wheel to the roll shaft was computed as 27.71mm from eqn. (48) given as (Bhandari, 2012):

$$d_{pm} = \frac{2M_t}{l \times \tau_{cpin} \times d_{s,pin}} \qquad (48)$$

Where,
M_t = torque transmitted = 5088410Nmm
l = length of pin =72mm
$\tau_{c,pin}$ = allowable shear stress = 85N/mm^2
$d_{s,pin}$ = shaft diameter = 60mm.

2.3 Assembly and mounting of machine components

The various stages of assembly and mounting of the machine components are shown in plates 1-4.

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Plate 1: Back view of the three roller bending machine

Plate 2: Front view of the three roller bending machine

Plate 3: Picture showing the electric motor and jacking bolts for chain adjustment

Plate 4: Picture of the gears assembly with keys installed

2.4 Machine Description

The motorized three-roller plate bending machine consists of six main parts: the frame; the 3- rolls; shafts; the roll screws, the control panel; the speed control system (consisting of gears, chain drive and control panel) and the electric motor. The electric motor drives the driver gear that controls the main roll which is connected to the driven roll thus taking the sheet of metal to be rolled. The frame was also constructed with ultimate stability and cares to avoid fracture or breakage owing to the weight of the rollers, the electric motor, the gear system and other peripheral components. This was done to ensure maximum safety for the user.

2.5 Working principle:

According to the principle of the three-point forming circle, the relative position change and rotational motion of the working roll make the metal sheet produce continuous plastic deformation to obtain the predetermined shape of the work piece. Three rolls bending machine usually take two lower rollers as active roll, can realize positive

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and reverse rotation. One upper roller is a follower roll, can move vertically up and down. When rolling steel plate is placed between the upper and lower rollers, and the three cutting points that are exposed to the metal sheet by three rolls can make the plate behind into a curved closed circle. Therefore, the forming process of sheet metal can be regarded as the three- roll bending machine to make a continuous three-point bending process. During processing, one end of the metal plate is feed into three-roller plate between the upper and lower roller, and then top roller bring downward displacement on the metal plate, which make the plate under it generate a certain plastic bending deformation due to compression. When the roller is rotating, there is friction between the plate and toll, so when the roll is rotated, the plate also moves along its longitudinal direction. Lower roller under positive and negative rotation alternately and rolled plate move back and forth, two lower roller rotation and the friction drive plate and roller move meanwhile, the upper roller continue to add downward pressure on the roller, the upper roller moves back and forth on the plate. When the plate pass the bottom of upper roller (the roller deformation zone) in turn, and stress exceeds the yield limit, it will produce plate deformation, the plate obtained the plastics bending deformation along the full length, and processed into the required shape. Adjust the relative position between the upper and lower rolls properly, and the plate can be bent to a radius not less than the radius of the upper roller.

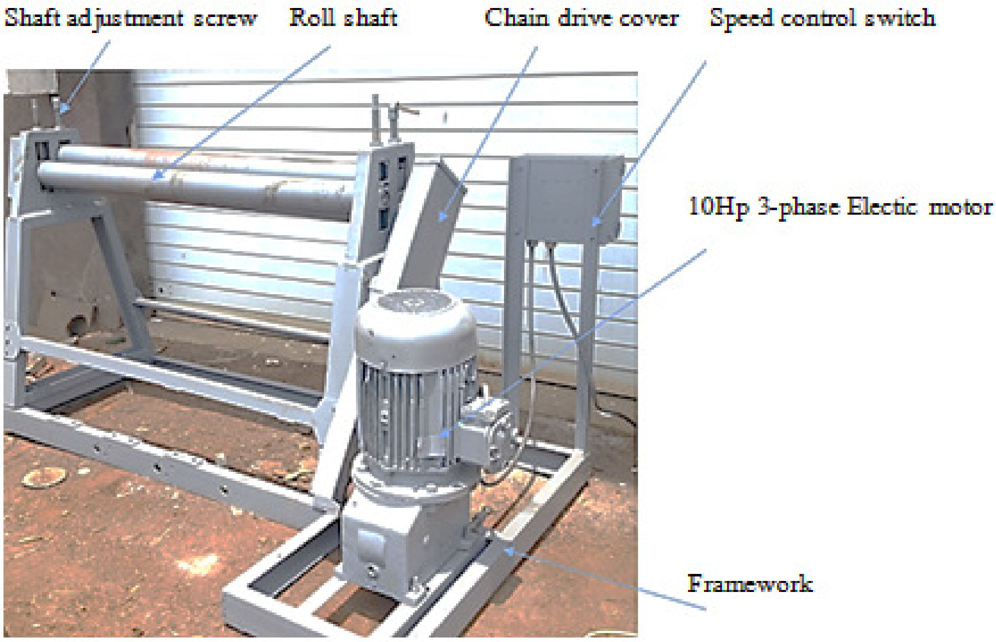

Plate 5: The 3-roller plate bending machine fabricated.

3. Results and discussion

3.1 Results

The summary of results of the machine components design is shown in Table 1.

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Table 1: Summary of results of machine components design

S/N	Machine components	Component description	Values
1	Sheet metal plate	Maximum thickness of plate	6mm
		Maximum width of plate	1219.2mm
		Maximum roll diameter	2400mm
		Bend allowance	0.434m
		Maximum bend radius	2.035m
		Minimum bend radius	0.018m
		Springback effect	0.21mm
2	Electric motor	3- phase gear motor	10Hp
		Motor speed	28rpm
3	Chain drive	Centre distance	1000mm
		Transmission ratio	2
		Drive sprocket teeth	34
		Driven sprocket teeth	17
		Chain type	Triple
		Chain pitch	38.1mm
		Chain speed	0.30m/s
		Pitch circle diameter of driver sprocket	207.3mm
		Outer diameter of driver sprocket	227.6mm
		Outer diameter of driven sprocket	433.2mm
		Chain length	69.78 links or 667mm
4	Spur gears	Transmission ratio	1.4
		Pinion teeth	20
		Wheel teeth=28	28
		Minimum centre distance between pinion and wheel	240
		Speed of pinion gear	14rpm
		Speed of wheel	10rpm
		Pitch line velocity	0.15m/s
		Module	10mm
		Face width	72mm
		Weight factor	1
		Bottom clearance	25mm
		Pitch circle diameters of pinion	200mm
		Pitch circle diameters of wheel	280mm
		Tooth depth	22.5mm
		Tip diameter of pinion,	220mm
		Tip diameter of wheel	300mm
		Root diameter of pinion	175mm
		Root diameter of wheel	255mm
5	Roll shafts	Shaft diameter	100mm
		Shaft speed	10rpm
6	Keys	Length of pin	72mm
		Diameter of pin	30mm

3.2 Discussion

Table 1 shows the values of the machine components obtained from the design. Figure 2 shows the exploded view of the machine parts, while Figure 3 shows the orthographic views of the 3-rolls plate bending machines. Plates 1-4 show the various stages of the assembly and mounting of the machine components, while the assembled machine is shown in plate 5.

4. Conclusion

The design and fabrication of a low cost motorized 3-rolls plate bending machine to bend a metal plate up to 6 mm thick mild steel plates has been carried. The major components of the machine designed were: the rolls shaft diameters; the chain drive; the spur gears drive and holding keys and the framework. Materials were selected to meet the machine requirements of strength, machine accuracy and reliability. The machine components were constructed by the various machining processes of cutting, turning and milling, and were thereafter arranged and joined together by appropriate joining methods such as welding and screw joints. The fabricated motorized 3-rolls plate bending machine with a 10hp electric motor is quite effective and efficient with maximum thickness of 6mm

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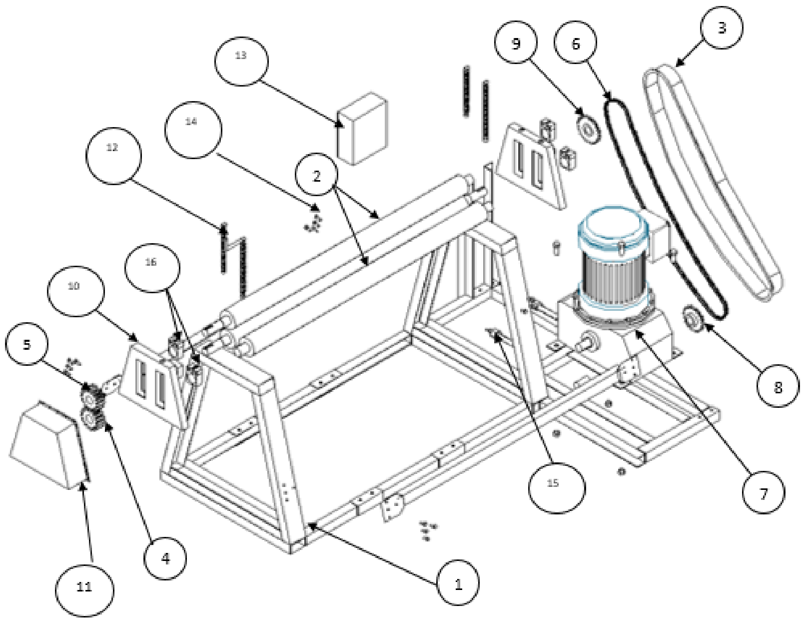
mild steel plate. The total cost of production is $1,363.64 which is relatively cheap compared to equivalent available in the market.



PARTS LIST		
Item#	Item Description	No. Off
1	Steel frame (U channel 50x100)	
2	Roller Shafts	
3	Sprocket Chain Cover	
4	Gear	
5	Pinion	
6	Chain	
7	Electric Motor	
8	Sprocket (Driver)	
9	Shaft Sprocket (Driven)	
10	Bushing	
11	Gear and Pinion Cover	
12	Screw	
13	Switch Box	
14	Hexagonal Bolt N Nut	
15	Tensioning Bolt	
16	Bushing	

Figure 2: Exploded view of the 3-rolls plate bending machine

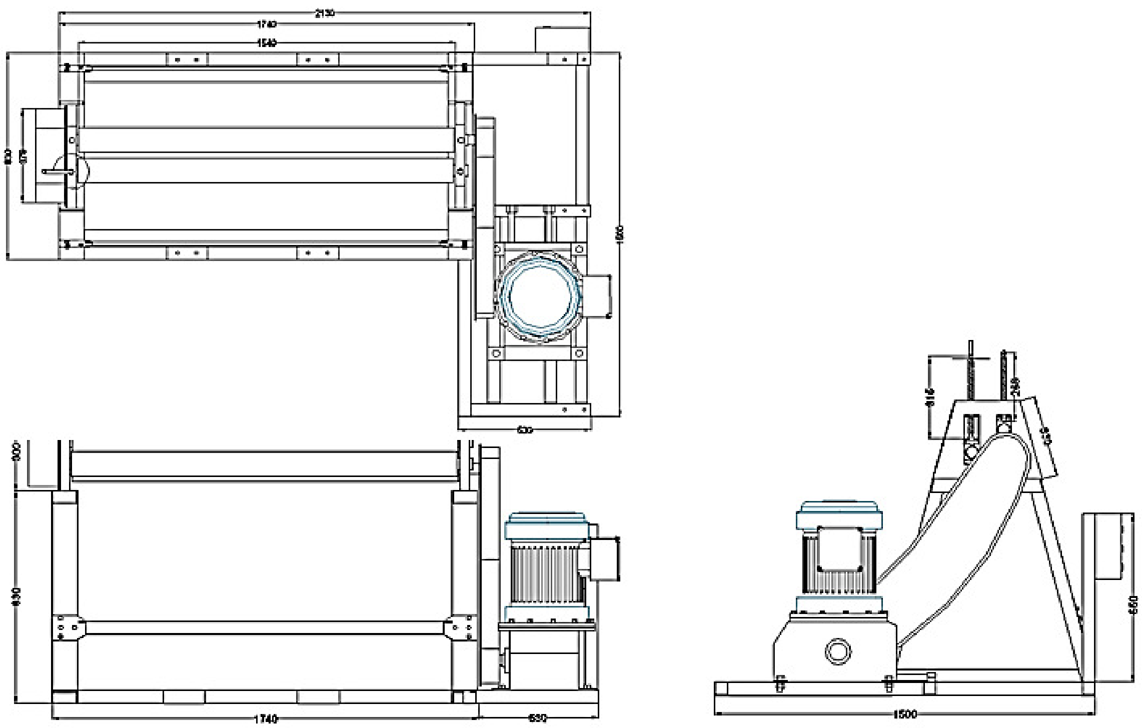


Figure 3: Orthographic projections of the 3-rolls plate bending machine

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