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Design and Fabrication of a One Stand Hot Tandem Rolling Mill

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This work was carried out in collaboration among all authors. The authors have read and approved the revised manuscript.

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ABSTRACT

Over the years, metalworking processes have emerged as a promising paradigm to modify materials' intrinsic workability and microstructural evolution. However, due to the stringent requirement of the state-of-the-art, non-uniform original grain structure of the metal ingot comprising large columnar grains growth in the direction of solidification, resulting in brittleness, weak grain boundaries, shrinkage, porosity, etc. remain a major bottleneck. This paper proposes a novel metalworking process to overcome this challenge. In particular, a one-stand hot tandem rolling mill that can break the grain structure and destroy the boundaries having uniform grain structures is developed. The proposed one-stand hot tandem rolling mill was constructed using 60 mm diameter work rolls, 150 mm diameter backup rolls, 120 mm diameter spur gears, a 3 hp electric motor, and a 50 mm diameter shaft. The components were installed, and the roll was fixed at a roll gap of 60 mm. Experimental investigations using a 65 mm aluminium sheet metal at a draft of 5 mm per pass after heating the metal sheet above its re-crystallization temperature were performed to validate the superiority of the proposed model. Available results indicate a robust improvement in the toughness, strength, and resistance of materials. Specifically, the results showed an efficiency of 86 % at an average draft of 4.3mm per pass.

1. Introduction

The metal rolling process finds its applications in several areas comprising automotive structural parts (e.g., frames), agriculture equipment, bearing and turbines rings, tabular products (e.g., gas cylinders and pipe), steel sheets, threaded parts (e.g., bolts and screws), rods and seamless hollow tubes. Rolling in metal working is a metal-forming process wherein the thickness of the metal stock is reduced while ensuring uniformity [1, 2]. Rolling processes are broadly categorized either based on roller arrangement and the number of rolls or the temperature of the metal during rolling.

On the working temperature, rolling processes are either hot or cold. In hot rolling, large pieces of metal (e.g., steel billets or slabs) are heated above their recrystallization temperature [3] to plastically deform it between rollers creating thin cross sections. It reduces the average grain size of metal but maintains an equal microstructure. Cold rolling usually requires several rolls to achieve the desired shape. Also, since the rolling process is done below the metal recrystallization temperature, it is less malleable compared to the hot worked metal. Interestingly, hot rolling enhances strength and toughness, resistance to shock and vibration, ductility, formability and weldability of materials. However, cold rolling is often implemented after hot rolling to attain

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enhanced mechanical properties, special sizes, better machinability, bright surfaces, as well as a thinner gauge compared to hot rolling [4].

Rolling mills are designed as 20-hi, 12-hi, 8-hi, 6-hi, 4-hi, 2-hi, tandem, and cluster rolling mills based on roller arrangement and number of rolls. The thinner sheets (2 to 3 microns) can be produced by a 20-hi rolling mill with fewer speeds, whereas the thicker sheets (4 to 10 microns) can be produced by a 4-hi or 6-hi rolling mill with higher speeds. The roller arrangement and number of rolls, which decide the speed and the maximum reduction in the rolling mill are described in the literature [1]. A tandem rolling mill is a special kind of mill where rolling is done in one pass. It employs more than two sets of rollers on each side of the metal sheet. There are one or more stands and reductions take place sequentially in each stand as shown in Fig. 1 [5].

An extensive overview of related literature in this domain is provided in this context. While considerable research attention has centred on various types of rolling mills, the tandem rolling mill has attracted little interest from the research community and industry. Ďurovský [6] studied the correlation between friction forces on single-stand rolling mills using genetic algorithms. In particular, the Bland ford technique was employed for the tandem rolling mill. The research thread is targeted at superimposing the flatness, thickness, speed and tension with the value of flatness for different hardness materials using the results obtained from the study. The authors in [7] have demonstrated the significance of rolling lubrication and coolant employed in the process of cold rolling. The study was performed on the premise of laboratory simulation and the actual temper rolling process. The results obtained indicate a modest boost (20-40%) in the rolling lubricity and cold rolled surface cleanliness when using new rolling lubricant.

An insightful exposition of the behaviour and mechanism of defect formation is presented in [8]. The study remarked that defects resulting from cold plastic deformation could be assessed via deviation from the original geometric shape of the flat sheet. These variations are determined by different factors (such as technological process realization, available rolling equipment solutions, and applied roll (tool) solutions) which affect the tolerance and final shape of the sheet metal. The authors in [9] developed a novel mill model to reduce the diameter of the working rolls and provide the rotation through the bearing stand with five gear motors rated 15 kW. Available results indicate a moderate magnitude of elastic deformation and displacement of the mill rolls while rolling in the new mill. Results also suggest that the mill holds for high rigidity of mill rolls and the corresponding stresses occurring in the rolls do not go beyond the maximum allowed value of the ultimate strength for the material.

The work in [10] proposed two insightful high-rolling mills for reducing sheet metal ingot cross sections. The rolling mill was designed to roll a maximum width of 100 mm and a draft value of 0.25mm per pass. Results from the experimental analysis revealed that the proposed machine can roll materials with a hardness less than the roller material with a maximum load of 13 tonnes, including a safety factor of 1.75. The design and fabrication of a roll-forming mill are provided in [11]. As a step further, a disruptive roller design including top and bottom rollers was fabricated for the obtained flower pattern design and unfold length calculations. Despite the laudable progress realized in the last two decades, several unresolved practical issues exist. Most notable amongst them is the non-uniform initial grain structure of the metal ingot consisting of large columnar grains growth in the direction of solidification, resulting in brittleness, weak grain boundaries, shrinkage, and porosity [12]. To unlock the full potential of metalworking processes, insightful metalworking models are urgently needed to replace conventional schemes.

This paper proposes a novel one-stand hot tandem rolling mill to overcome the hurdles currently ravaging metalworking processes and guarantee performance maximization.

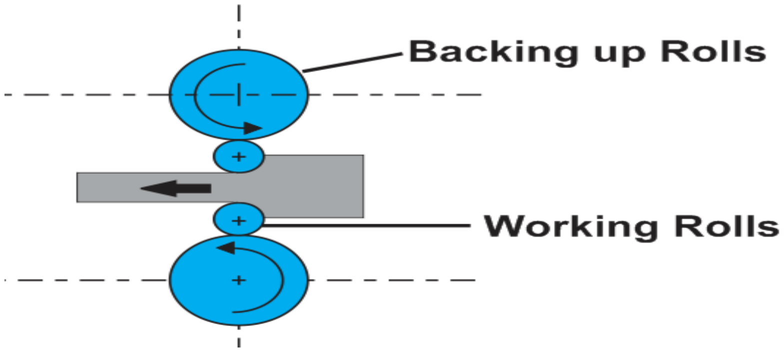


Fig. 1 Tandem rolling mill [5].

2. Materials and Methods

2.1. Material Selection

The material selection was based primarily on the function individual component would perform. It is worth mentioning that the strength, durability of the machine, and its ability to withstand failure lie in the physical, mechanical, and thermal properties of the materials to be used. Therefore, the frame, shaft, gearbox, gears, and roller were made of mild steel because of their strength, cost-effectiveness and availability. The bearings were made of high-carbon steel. To design and fabricate the rolling mill, the following materials were employed:

(i) 3 hp electric motor
(ii) Gearbox
(iii) Gear
(iv) Tool steel
(v) 150 mm mild steel pipe
(vi) Mild steel round bar
(vii) 4 mm angle iron bar
(viii) 2 mm mild steel sheet
(ix) Bolts and nut, 19 mm and 13 mm
(x) Coupling
(xi) Lubricant
(xii) Paint

2.2. Design Consideration

The main rolling parameters that affect the rolling process include roll diameter, deformation resistance of the metal, friction between rolls and workpiece, presence of roll tensions, and chatter.

Chatter refers to undesirable intense mill vibrations, which occurs in both cold and hot rolling process. It causes low-quality output and additional losses through the cost of nonconforming strips. Also, unsteady lubrication, rolling speed, and mechanical transmission system are some of the causes of chatter in a rolling mill.

The rolling load, F increases with roll diameter, D at a rate greater than half of the roll diameter as expressed in equation (1).

$$F = y_f(\sqrt{(D/2)\Delta H} \times W \tag{1}$$

Where y_f is the flow stress, D is the Diameter of the roll, ΔH is the draft, and W is the maximum rollable width of the ingot.

In the design of the rolling mill, several factors were taken into consideration to achieve optimal performance of the proposed machine. Special emphasis was given to the techno-economic feasibility of the machine. Different loads acting on the machine members (shaft, rollers, workpiece and mainframe) were considered. Consideration was also given to the roll force and torque acting on the shaft. Finally, the yield strength of the material being rolled was considered as it affects the rolling force.

2.3. Design Calculations and Analysis of the Machine

The methods employed in the design and fabrication of the four (4) high rolling mills include design, calculation, and analysis of the individual component, fabrication of parts, assembling of parts, finishing, engineering drawing of the working components, and testing of the machine to determine its functionality.

2.3.1Design specification: The following were used as the design standards:

(a) The maximum allowable thickness of the workpiece is 65 mm
(b) Maximum allowable width of the workpiece is 300 mm
(c) Length of the roll is 600 mm
(d) Work roll diameter is 60 mm
(e) Backup roll diameter is 150 mm

2.3.2Determination of draft: In flat rolling, the work is squeezed between two rolls so that its thickness is reduced by an amount called the draft (ΔH) and it is a function of the roll radius and coefficient of friction between the rolls and the workpiece [13]. The draft is expressed as follows [14]:

$$\Delta H = h_o - h_f = \mu^2 R \qquad (2)$$

Where h_o is the initial thickness of the workpiece (mm), h_f is the final thickness of the workpiece (mm), R is the roll radius, which is equal to d/2 (mm), d is the roll diameter, which is 60 mm, μ is the coefficient of friction between the rolls and the workpiece, which is taken as 0.4. Thus,

$$R = 60/2 = 30 \text{ mm} \qquad (3)$$

$$\Delta H = 0.4^2 \times 30 = 4.8 \text{ mm} \qquad (4)$$

For this design, a 5mm draft was used. The machine is expected to reduce the workpiece thickness by 5mm at one pass.

2.3.3Determination of roll gap: The distance between the work rolls is referred to as the roll gap and is taken as the final thickness of the workpiece. The roll gap is expressed as:

$$h_f = h_o - \Delta H \qquad (5)$$

$$h_f = 65 - 5 = 60\text{mm}$$

2.3.4Determination of the true strain of the aluminium sheet: The true strain (ε_t) is deduced using equation (6) [15].

$$\varepsilon_t = In\frac{h_o}{h_f} = \frac{h_o^2 - h_f^2}{2h_f^2} \qquad (6)$$

By substitution,

$$\varepsilon_t = \frac{65^2 - 60^2}{2(60)^2} = 0.087$$

2.3.5Determination of roll force: The roll force (F) required to reduce the material is given as equation (7) [16] whereas the flow stress is stated in equation (8) [13]:

$$F = y_f(\sqrt{R\Delta H}\,) \times W \qquad (7)$$

$$y_f = \frac{K{\varepsilon_t}^n}{1+n} \qquad (8)$$

Where W is the Maximum roll able width of the aluminium sheet (which is 300mm), y_f is the flow stress of aluminium (N/mm^2), K is the strength coefficient, n is the stain-hardening exponent, R is the roll radius (30mm), the draft (ΔH) is 5mm and the true strain ε_t = 0.087. At elevation temperature, the optimum value of K and n for aluminium are 120MPa and 0.2 respectively [13]; thus,

$$y_f = \frac{120(0.087)^{0.2}}{1+0.2} = 61.4 \text{ MPa}$$

$$F = 61.4(\sqrt{30 \times 5}\,) \times 300$$

$$F = 225.6\text{kN} = 22.56 \text{ tonnes}$$

2.3.6 Determination of torque required: The torque required is computed as [17]:

$$T = F \times \left(\sqrt{R\Delta H}\right)/2 \qquad (9)$$

$$T = 225598 \times (\sqrt{30 \times 5})/2 = 1381.5 \text{ Nm}$$

2.3.7Determination of angular velocity required: Hot rolling of aluminium requires low speed for good quality output. Forming rate of 0.2 – 5 m/min are desirable [8]. For this design, speed of 2.8 m/min (0.047 m/s) is used. The roll angular velocity is

$$\omega_r = \frac{V}{R} \qquad (10)$$

Where *V* is the forming speed of aluminium and *R* is the roll radius. Thus,

$$\omega_r = \frac{0.047}{0.03} = 1.57\text{rad/s}$$

The roll speed in rpm, becomes:

$$N_2 = \frac{60 \times \omega_r}{2\pi} \qquad (11)$$

$N_2 = \frac{60\times1.57}{2\pi} = 15$ rpm

The electric motor has an input speed of 2000 rpm, and the gearbox was designed to reduce the motor speed to the required roll speed of 15 rpm.

Input motor speed, $N_1 = 2000$ rpm

Roll speed, $N_2 = 15$ rpm

The gear transmission ratio is:

$$R_g = N_1/N_2 \tag{12}$$

$R_g = 2000/15 = 133.3$

It is difficult to reach the final speed of 15 rpm in one step. For this reason, the cube root of the transmission ratio was calculated.

$R_g = \sqrt[3]{133.3} = 5.1$

Therefore, the gears and pinions were constructed and arranged in such a way to attain the output speed in a single step.

2.3.8Determination of power required: The power required to operate the machine is given as [18]:

$$P = T\omega \tag{13}$$

T is the torque required (Nm) and ω is the angular velocity of the roller (rad/s), which can be stated as [13]:

$$\omega = \frac{2\pi N_2}{60} \tag{14}$$

Thus,

$$P = \frac{2\pi N_2 T}{60} \tag{15}$$

By substitution

$P = \frac{2\times\pi\times15\times1381.5}{60}$

$P = 2.17$ kW $= 2.91$ hp

For this design, a standard motor power of 3 hp operation at 2000 rpm was selected.

2.3.9Design for roll shaft: The roll shaft is a solid shaft and transmits power from the electric motor to the machine rolls via the gears. The bending moment diagram of the shaft is shown in Fig. 2.

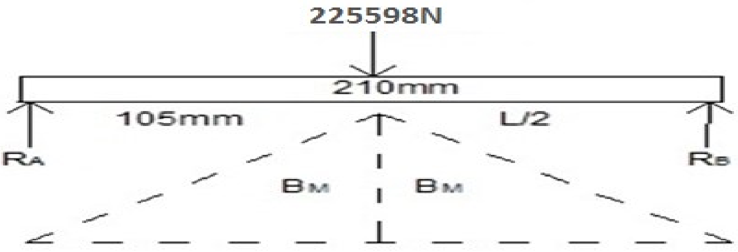


Fig. 2 Bending moment for the shaft.

The reaction forces (R_A) and (R_B) are due to the bearing supports acting on the shaft. The roll force acting on the shaft is assumed to be concentrated. The maximum bending moment occurs at

$$M_{max} = \frac{FL_s}{4} \tag{16}$$

Where F is the roll force acting on the shaft and L_s is the length of shaft. Thus,

$M_{max} = \frac{225598\times210}{4} = 11843895$ Nmm

The diameter of the shaft is determined using equation (17)

$$d_s = \left(\frac{32}{\pi y}\sqrt{[(M_b)^2 + (M_t)^2]}\right)^{1/3} \tag{17}$$

Where; d_s is the diameter of shaft (mm), M_b is the bending moment (Nmm), M_t is the torsional moment of the shaft or torque (= 1381500 Nmm) and y is the Mean yield strength (MPa). The mean yield strength of mild steel was taken as 250 MPa for shafts with allowance for keyways [18].

$$d_s = \left(\frac{32}{\pi \times 250}\sqrt{[(11843895)^2 + (1381500)^2]}\right)^{1/3}$$

$$d_s = \left(0.041\sqrt{[1908542250000]}\right)^{1/3}$$

d_s=$(56641.5)^{1/3}$ = 36.3 mm

A standard roll shaft of 50 mm diameter was used for this design.

2.4. Fabrication Process

The engineering drawing of the machine was done using AutoCAD software. The isometric modelling, and exploded component drawings of the machine are shown in Fig. 3.

2.4.1Frame: The frame acts as support for other components of the machine. The frame is made of 3mm angle and flat mild steel bars. The frame is rectangular in shape with a dimension of 1525 mm × 650 mm × 400 mm, and total height of 1200 mm from ground level, having the strength and rigidity to withstand the load. The mild steel materials were marked out and cut into sizes using power saw. The cutting operation was followed by drilling and welding of the pieces to form the frame part. Drive mechanism stand measuring 1300 mm × 400 mm was incorporated on the front side of the machine frame.

2.4.2Roll shaft: Shaft is a machine member used to transmit power in a machine. It is a solid motor shaft connected to the gear box to drive the rolls. It was made of round mild steel bar. The shaft was produced by cutting the mild steel material to the required length of 210 mm and subsequently turning in a lathe with some tolerable clearance to get the desired shape and size. Key ways were produced on the shaft followed by machining operation to complete this process. The shaft has a diameter of Ø50 mm.

2.4.3Work and backup rolls: The machine employs two work rolls (main rolls) and two backup rolls (support rolls). The rolls were fabricated using hardened tool steel. In this process, the round tool steel bar was cut to the required dimension. The pieces were turned in lathed to the required shape and size, followed by drilling and machining. The work rolls and the backup rolls were fabricated having diameters of 60mm and 150 mm, respectively.

2.4.4Sun gears: Gears are used for rotational speed variation. The sun gears were produced in the lathe, drilling, and milling machines. The materials for the sun gear (mild steel round bar) were cut to the required sizes using a power saw. The pieces were turned in a lathe to the required dimension and then transferred to the drill machine to bore holes. The gear teeth were produced in a milling machine and the parts were machined for a good surface finish.

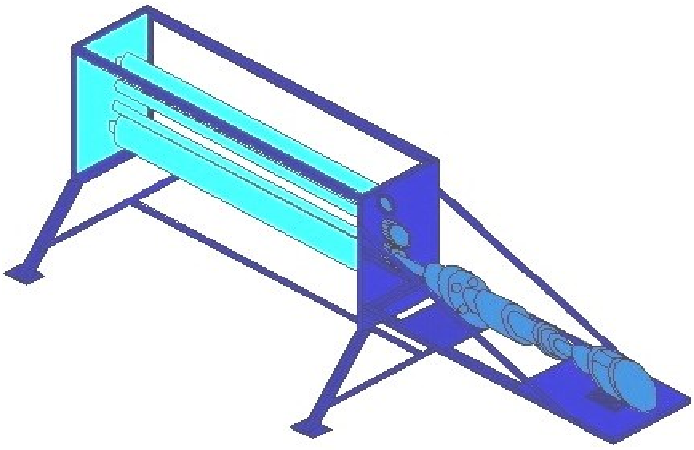
2.4.5Drive mechanism: The drive mechanism consists of gears, a rotor shaft, an electric motor, bearings, couplings, and gearbox. The electric motor, bearings and couplings were purchased due to the hi-tech and precision involved in their manufacturing.

2.4.6Assembling and finishing process: The assembling process involves joining the different parts of the machine together. In this process, the drive mechanism which comprises the electric motor, gearbox, and shaft was installed together to form a unit and was mounted on the drive mechanism stand. The rollers were installed on the machine base. They were mounted in such a way that the machine can only process work pieces 30mm thick. The drive mechanism and the rollers were interconnected via shaft, bearings, gears, and couplings. The finishing process was carried out on the machine to improve surface finishing and corrosion control which adds value to the machine. In addition, a machining operation was carried out to free the joints and surfaces from scraps.

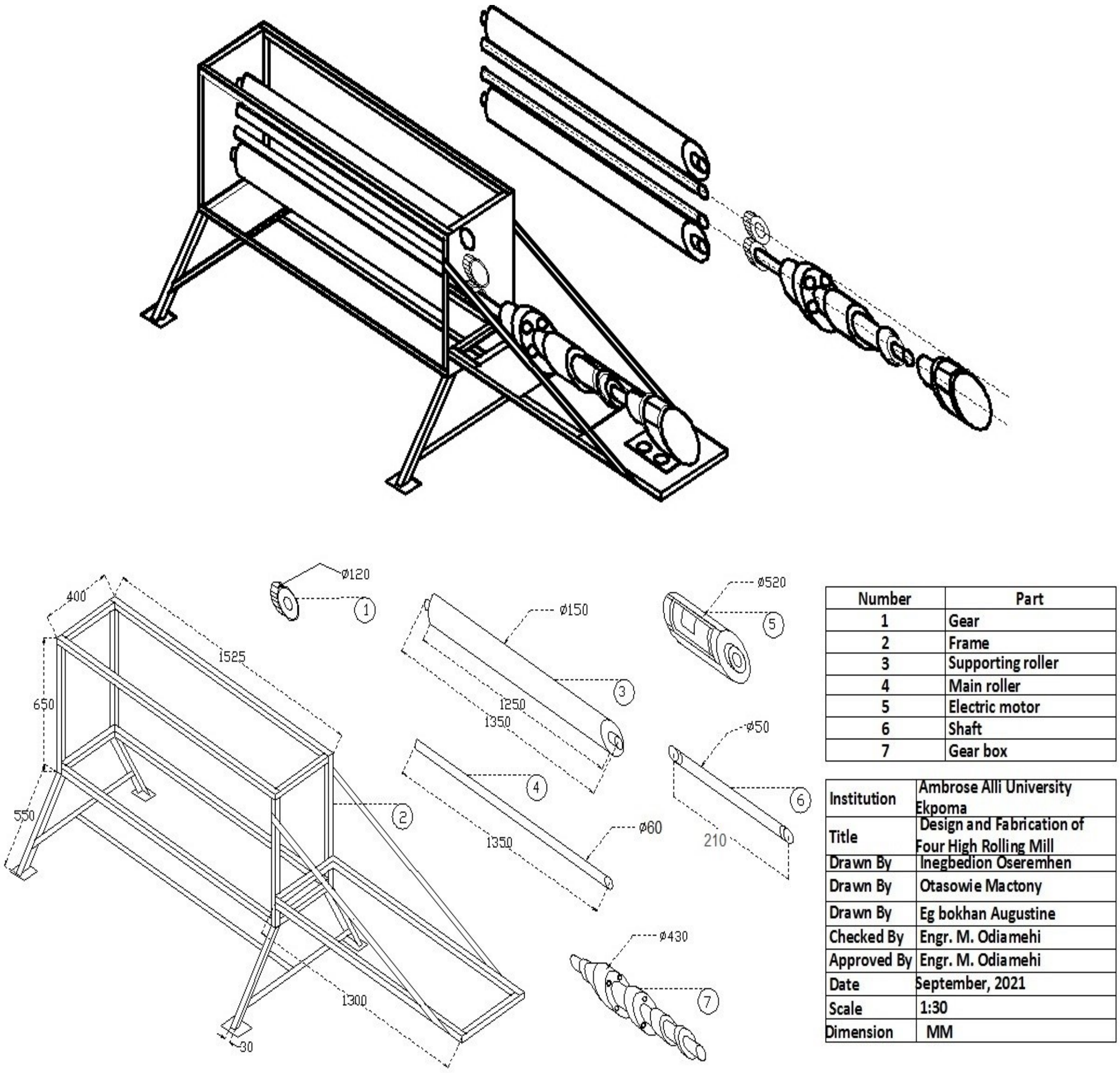
2.5. Performance Test of the Machine

Five samples were prepared for the test. The machine was tested with an aluminium sheet of width 300 mm and thickness 65 mm. Before the testing, all the moving parts of the machine were lubricated to reduce friction. The aluminium samples were heated above their recrystallization temperature of 330 °C using a crucible furnace. The machine was switched on and each sample was immediately placed on the machine after heating for testing.

After one pass, the final thickness of the sample was measured and recorded. The test was repeated five times and the values obtained are recorded.



(a)



Number	Part
1	Gear
2	Frame
3	Supporting roller
4	Main roller
5	Electric motor
6	Shaft
7	Gear box

Institution	Ambrose Alli University Ekpoma
Title	Design and Fabrication of Four High Rolling Mill
Drawn By	Inegbedion Oseremhen
Drawn By	Otasowie Mactony
Drawn By	Eg bokhan Augustine
Checked By	Engr. M. Odiamehi
Approved By	Engr. M. Odiamehi
Date	September, 2021
Scale	1:30
Dimension	MM

(b)

Fig. 3 Components of the Rolling Mill (a) Isometric Modelling and (b) Exploded View of the Machine.

3. Results and Discussion

The fabricated one-stand hot tandem rolling mill is shown in Fig. 4. The results obtained from testing the one-stand hot tandem rolling mill with aluminium sheet metal are presented, for simplicity, in tabular form (Table 1) with the corresponding chart in Fig. 5. Table 2 presents the machine specification.

The machine's performance was evaluated based on draft efficiency as

$$\varepsilon = \frac{Actual\ draft}{Designed\ draft} \times 100\% \tag{18}$$

$$\varepsilon = \frac{4.3}{5} \times 100 = 86\%$$

Table 1 Summary of the Test Results.

No.	Width of Al Sheet (mm)	The Initial Thickness of Al Sheet (mm)	The Final Thickness of Al Sheet (mm)	No. of pass	Draft (mm)
1	300	65	60.7	1	4.3
2	300	65	61.0	1	4.0
3	300	65	60.7	1	4.3
4	300	65	60.8	1	4.2
5	300	65	60.4	1	4.6
Average	300	65	60.7	1	4.3

Table 2 Specification of the Developed Rolling Mill.

Parameter	Specification
Power rating	3 HP, 220V AC
Efficiency	86 %
Draft capacity	4.3 mm/pass
Roll force	22.6 ton

Fig. 4 Pictorial view of the Fabricated one-stand hot tandem rolling mill.

From Table 1, the final rolled thickness varied from 60.4 mm to 61 mm. The values obtained from the test did not follow a particular trend as shown in Fig. 5. The highest rolled thickness was recorded for sample two (61 mm) and the lowest for sample five (60.4 mm). Also, the draft ranged from 4mm to 4.6mm and the highest draft was recorded for sample five having a value of 4.6 mm and the lowest for sample two (4 mm). The average rolled thickness and draft obtained per pass were 60.7 mm and 4.3 mm respectively. The machine has a draft efficiency of 86 % when tested with aluminium sheet metal. A smooth surface was obtained when used to process the aluminium ingot. This was due to the uniformity and surface smoothness of the rolls coming in contact with the material surface. This distinctive benefit is afforded due to the rolling action of the electric motor and shafts. Fortunately, the whole operation was very fast (one minute per pass). The bill of engineering for the measurement and evaluation of the machine is shown in the appendix (Table A).

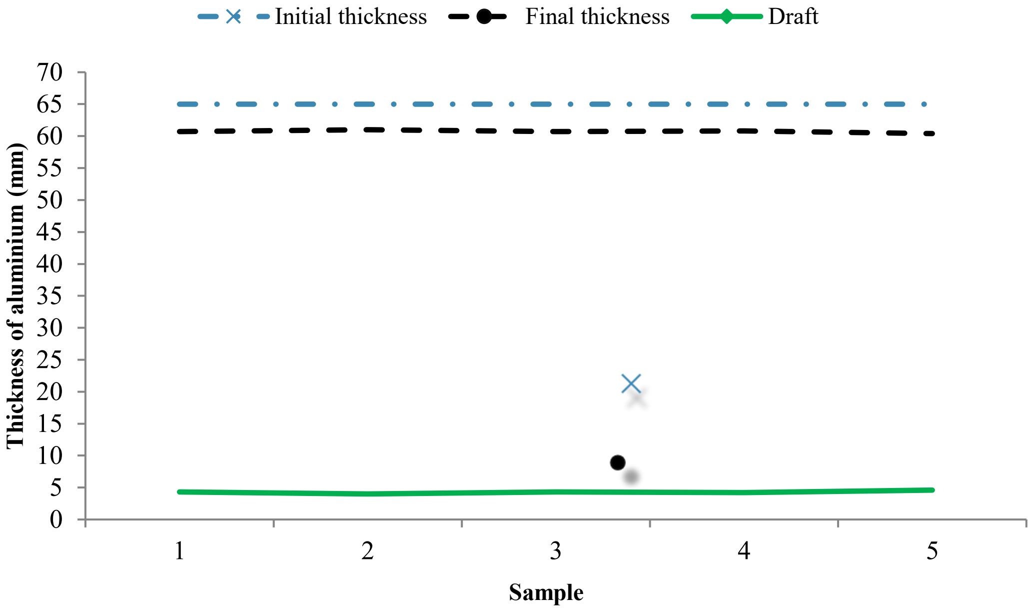


Fig. 5 Thickness variation of the aluminium samples.

4. Conclusion

In this paper, a one-stand hot tandem rolling mill designed to roll aluminium sheets was proposed. The work and support rolls were made of tool steel with diameters of 60mm and 150mm, respectively, which can roll materials with hardness less than the roller material subject to a maximum load of 22.6 tons. The rolls were driven by a 3 hp motor operating at 2000 rpm with an output speed of 15 rpm. Insightful results reveal a draft efficiency of 86% and an average draft of 4.3 mm per pass. Besides, the proposed model is shown to be highly flexible with less operational time and economically viable in comparison with imported ones. Going forward, the rolling mill can be dynamically deployed in industrial applications for rolling aluminium sheet metal.

Appendix

Table A Bill of Engineering Measurement and Evaluation.

Parts	Description	Size/Model	Quantity	Cost (₦)
Electric motor	Power	3 hp	1	55,000
Gearbox	Speed control	-	1	44,000
Sun gear teeth	Speed	-	2	20,000
Block bearing	Support	Ø120 mm	8	24,000
Mild steel pipe	Roller	6 inches	2	50,000
Angle iron	Frame	4 mm	3	18,000
Mild steel sheet metal	Frame	2 mm	½	10,000
Bolts and nuts	Parts joining	19 mm, 13 mm	16	11,000
Paint	Surface finish	Oil	-	12,000
Grease	Lubrication	-	1 cup	3,000
Coupling	Parts joining	-	-	3,000
Shaft	Power transmission	50mm	2	20,000
Miscellaneous	-	-	-	30,000
Total				300,000

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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