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Performance Assessment of A Developed Rolling Mill

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ABSTRACT

Rolling of metals has found applications in automotive, construction, agriculture, railroads, housing, metal furniture making, home appliances, electronic cabinetry, pipes and tubing etc. These have as well contributed to human and environmental sustainability. Nevertheless, the applications of metal rolling processes and machines have not been adequately harnessed in our locality due to unavailability of the rolling machine in small scale industries, laboratories and workshops in institutions of learning in the region. Annealing heat treatment was carried out on a mild steel round bar of 50 mm diameter and length of 200 samples. The samples were charged into an SXL muffle furnace with an annealing temperature of 950^{o}C. The mechanical properties and the microstructure of the rolled mild carbon steel were evaluated. The results of the performance evaluation of the machine through assessment of the metallurgical characteristics of the rolled products from the machine and assessment of mechanical properties such as tensile strength and hardness of the rolled products from the machine showed an increase in the tensile strength from 250.85 MPa to 258.85 MPa, an increase in the ultimate tensile strength from 535.88 MPa to 540.05 MPa, an increase in the hardness from 140 HV to 145 HV, and a decrease in the percentage ductility of the mild carbon steel from 56% to 51%. Also, the optical micrograph of the rolled samples shows a coarse microstructure of grain refinement from slipping and pilling of dislocations.

Keywords: Rolling mill; heat treatment; mild carbon steel; hardness; tensile strength

INTRODUCTION

Manufacturing of machines and its components with unique capabilities to meet human and environmental needs and challenges have led to increased research and development of technologically advance machine components. Rolling as a secondary manufacturing process is applied in the metal working industry to produce varying shapes and strength of metallic materials. The process has great influence on material properties including machinability, ductility, brittleness, surface hardness, microstructure, corrosion resistance, notch sensitivity and lot more. Control of these materials properties during manufacturing determines final product characteristics. Furthermore, understanding the effects of the process parameters of rolling processes on the mechanical and metallurgical attributes allows the development of metals with specific engineered properties (Hongchun et al. 2007; Leonard, 2014). By this, the rolling mill has become an important metallurgical tool not only able to achieve final product shape, but also to produce higher strength micro alloyed metals and alloys through grain refinement (Mahfouf et al. 2004; Leonard 2014)

Rolling is the plastic deformation of materials caused by compressive force applied through a set of rolls (Soszyński and Studnicka 2012). Rolling is used in the sheet metal industry to reduce thickness and change the cross-section of a long work piece by applying compressive forces through a set of rollers (Schindler et al. 2009). Here, the material gets squeezed between a pair of rolls, as a result of which the thickness gets reduced and the length gets increased (Heidepriem et al. 1998; Hariharan et al. 2018). Hot rolling and cold rolling are both methods of metal rolling. Hot rolling uses large pieces of metal, such as slabs or steel billets, and heats them above their recrystallization temperature. The metal pieces are then deformed between rollers, creating thin cross sections. These cross sections are thinner than those formed by cold rolling processes with the same number of stages. Hot rolling also reduces the average grain size of metal but maintains an equal microstructure (Maklakova et al. 2015). Most rolling is carried out by hot working, called hot rolling, owing to the large amount of deformation required. Hot-rolled metal is generally free of residual stresses, and its properties are isotropic. Work begins with a cast steel ingot that has just solidified in metal rolling, for example, in steel making. While it is still hot, the ingot is placed in a furnace, where it remains for many hours until it has reached a uniform temperature throughout so that the metal will flow consistently during rolling. The heating operation is called "soaking," and the furnaces in which it is carried out are called "soaking pits." After soaking, the ingot is moved to the rolling mill, where it is rolled into one of three intermediate shapes called blooms, billets, or slabs.

Generally, metals are usually very difficult to work on during machining processes, thus, the need for heat treatment to soften the metal so that various machining operations can be carried out on it (Onyekpe 2002; Abbasi et al. 2015; Abdulrasak et al. 2018; Masoud, 2018; Ogedengbe et al. 2022; Orhorhoro et al. 2022;). In the metal casting process, most metals usually have gases, annealing such a metal will help remove the trapped gases between its layers (Sanij et al. 2012; Hamza et al. 2019; Mondal et al. 2020). Annealing, as the name implies, is a heat treatment process that changes the physical and sometimes chemical properties of a material to increase its ductility, soften the given material, relieve its internal stress, refine the structure by making it homogeneous so as to improve its cold working properties, and make it more workable (Raji and Oluwole 2012; Tukur et al. 2014; Abdulrasak et al. 2018; Orhorhoro et al. 2018; Oluwagbenga et al. 2019). The use of mild carbon steel is vital to almost all aspects of human endeavor. Our human civilization cannot exist without steel. The two particular reasons for the extraordinary versatility of steel are heat treatment and alloying. Heat treatment and alloying are the two main reasons for steel's exceptional flexibility. Heat treatment is a heating and cooling operation performed on metals and their alloys in a solid state in order to influence the required properties of the metal and its alloy (Sharma 1998; Nora et al. 2020). Metal heat treatment is a critical step in the final manufacturing of many engineering components (Al-Quran and Al-Itawi, 2010). Heat treatment is applied to metal alloys to improve their mechanical properties. In general, product performance improves as material strength increases (Fadare et al. 2011). Annealing, quenching, and tempering are all part of the heat treatment process. Annealing is a heat treatment procedure that affects the qualities of a material such as strength and hardness. It is a procedure that creates conditions by heating above the critical temperature, maintaining a proper temperature, and then progressively cooling (Rajput, 2004). Mild carbon steel annealing is primarily used to increase ductility, soften materials, relieve internal stresses, refine the structure by making it homogeneous, and improve cold working capabilities (Isfahany et al. 2011). Carbon steel is annealed for the following reasons (Rajput, 2004): to soften the metal, enhance machinability, relieve internal tensions, eliminate gases, generate a distinct microstructure, adjust electrical and magnetic characteristics, and to increase corrosion resistance.

However, the mechanical properties of mild carbon steel are affected after mill rolling. Thus, understanding the behavior of the steel when mill rolling is performed on it is critical, as this will help to reduce losses knowing that millions of naira can be lost. Therefore, this project will help solve the following problems:

1. to investigate the effect of rolling to the tensile properties and surface hardness of the mild streel sample
2. of local manufacturing processes thereby resulting through the use of locally manufactured and improved work tools and machines
3. ability to roll all type of metals
4. to observe and compare the surface morphology of the mild steel before and after rolling.

MATERIALS AND METHODS

The materials used in the fabrication of the rolling mill consists mainly of carbon steel. The materials were prepared according to the designed features using the common fabrication processes. To ensure high integrity of welded joints against failure especially the roll carrier parts, Lincoln 6010, φ2.5mm low hydrogen electrode was used for penetration of prepared joints and a 7018, φ4mm low hydrogen electrode applied for filling and capping with a 500 amps Kaleida DC welding machine. Other major parts of the rolling mill such as gears, bearings, electric motor, steel rod and other parts were purchased as specified in the design (Table 1). An industrial lathe machine, grinding machines, portable drilling machine and other equipment and tools were used.

TABLE 1. Design Specification and Justification of Material Used

No	Components	Specification	Basis	Material	Justification
1	Frame	Angular mild steel bar of cross section 1290.60 mm x 917.27 mm x 787.40 mm	For support and provision of rigidity for the machine and help in preventing failure	Carbon steel	ASTM specification
2	Main Shaft	φ 90 mm x 800 mm	High wear resistant and strength, machinable and transmission of torque	Stainless steel	Ability to absorb shear force and compressive force. Good corrosion resistance ability
3	Electric motor	10hp	Effective power consumption at minimal cost	N/A	The operational system of the machine requires low speed electric
4	Gear	Driver: φ 175 mm Teeth: 21 Driven: φ 350 mm Teeth: 38	Ability to withstand strength and service condition such as wear, noise, etc.	Cast iron	Excellence machinability and easy of producing complicated shapes by casting method.
5	Roll	φ 254 mm cylindrical in shape	Strength and toughness	High carbon steel	Excellence machinability and easy of producing complicated shapes by casting method.
6	Bearing	φ 90 mm	Toughness and strength	Stainless steel	Ability to withstand wear, and fatigue failure
7	Design Life	Active Life	Life span of the machine	N/A	Compensation for total cost of the machine and quality of materials used.
8	Machine Cost	Minimum cost and Affordability	An overview of the fabrication cost	N/A	For Commercialization and training purpose

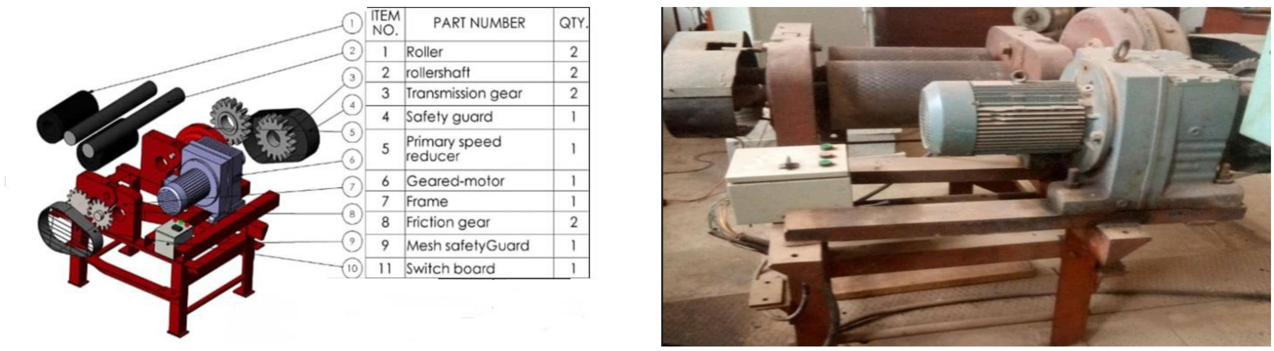

FIGURE 1 (a) Exploded view of rolling mill and (b) Fabricated Rolling Mill

The developed rolling mill was evaluated for performance using a mild steel round bar of 50 mm diameter and length of 200 mm purchased from a local market in Nigeria. The determination of the chemical composition of the mild carbon steel used in this research work was carried out at Donasulu brothers Nigeria Limited, 67 Effurun/Warri roads opposite Edewor shopping centre, Effurun/Warri, Delta State, Nigeria. The result of the chemical composition of the mild carbon steel samples used for this investigation is shown in Table 2. The mild carbon steel was machined at the Igbinedion university college of engineering workshop. Annealing heat treatment was carried out on the machined samples. The samples were charged into an SXL muffle furnace manufactured by Meditry Instrument Co., Ltd., with an annealing temperature of 950^{o}C. The annealed samples were then soaked at a temperature duration of 60 minutes.

Tensile test was carried out on the heat-treated specimens using ASTM D638 standard. Mechanical testing was conducted on the control, annealed heat treated, and rolled mild carbon steel samples. The mechanical properties evaluated included; yield strength, tensile strength (ultimate tensile strength), percentage (%) elongation or elongation to failure (ductility) and hardness. These tests were done in accordance to ASTM B557 specification. Tensile testing of all the specimens was conducted at room temperature with a cross head speed of 5 mm per minute using a Universal Tensile Testing Machine (600kN Max. Load, Avery-Denison made). The annealed rolled mild carbon steel samples were subjected to hardness test according to ASTM E92-82 using Micro-Vickers Hardness Tester (Model: MV1-PC). This test was conducted at Shell Professorial Chair Office Complex, Ahmadu Bello University, Zaria. A diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces applied a load of 3kgf to the test material using a dwell time of 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load were measured using a microscope and their average calculated.

Specimens of the control, solution heat treated only, aged and cold rolled were subjected to microstructural analysis by metallography technique and then examined by an optical microscope. These specimens to be analyzed were prepared by sectioning and mounting, grinding, polishing and etching of the surface. The specimens to be examined were first sectioned at the midpoint and then mounted on a holder. Grinding operation was aimed at producing a perfectly flat and smooth surface. We used Silicon Carbide grinding papers of different grades ranging 320, 400 600, 800 and 1200 (i.e., from coarse grade to fine grade) placed on the grinding to remove as much layer as possible and also to expose where the true microstructure is. The grinding process was done under running water to wash away the grits and also to avoid overheating. The samples were rotated through 900 while changing from one grit size to another. This is to neutralize the scratching effect of the previous grinding of the former grit size. Polishing was done to remove the traces of last scratches left during grinding. A polimet polishing machine with bronze wheel on which polishing cloth (velvet cloth) was placed and secured. Alumina polishing powder was dissolved in distilled water to the required concentration (50mg/50ml of distilled water) to wet the polishing cloth, after which the machine was switched on to rotate anticlockwise while polishing was done clockwise until a scratch-free mirror-like surface was attained. It was then washed and dried. This was done to reveal the microstructure of the material by removing the layer of the polished surface. The mirror-like surfaces were etched in Keller solution which is 190ml distilled water, 5ml Nitric acid, 3ml Hydrochloric acid, and 2ml Hydrofluoric acid, for 10 to 30 minutes. After which, the specimens were washed in running water and dried using air blower. An optical metallurgical microscope with a 100-pixel magnification and fitted with a photographic device was used to view and record the etched surfaces. The etchant used ensured that the second phase precipitates appeared as darkened portions. This was also carried out with a scanning electron microscope with a 1000-pixel magnification.

RESULTS AND DISCUSSION

Table 2 shows the results of the chemical composition of the mild carbon steel sample used in this research work.

TABLE 2. Chemical Composition of Mild Carbon Steel Sample (wt. %)

Element Present	Percentage Weight (%)
Carbon (C)	0.16
Silicon (Si)	0.29
Manganese (Mn)	0.85
Phosphorous (P)	0.025
Sulphur (S)	0.027
Copper (Cu)	0.33
Nickel (Ni)	0.04
Chromium (Cr)	0.07
Molybdenum (Mo)	0.004
Aluminum (Al)	0.023
Tungsten (W)	0.005
Nitrogen (N)	0.005

It was observed that rolling improves the hardness properties of the mild carbon steel material, as depicted in Figure 2. Rolling produces an increase in hardness from 140 HV for as-received material to 145 HV. The increase in hardness could be the result of the introduced dislocations, as reported by (Sech et al. 1990) and (Shen et al. 2008). Furthermore, temper hardness is generated as a result of deformation hardening, which affects material formability during the stamping process. Although this procedure has its advantages, the rolling of metals generates plastic strains by the motion of dislocations, and the interaction and multiplication of dislocations lead to an increase in the resistance to plastic flow through which such metals are strengthened and shaped. On the contrary, the ductility of the mild carbon steel decreased, and this was attributed to the dislocation movement.

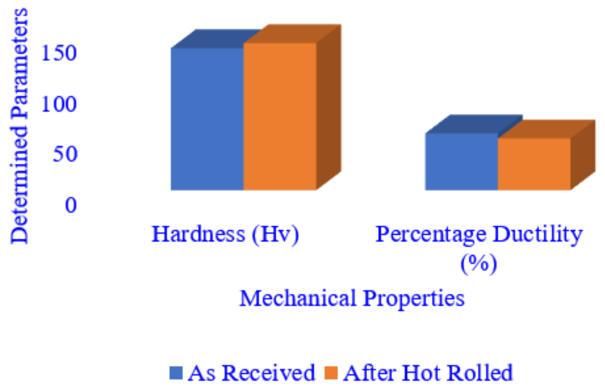

FIGURE 2. Evaluation of the hardness and ductility of annealed rolled mild carbon steel

Furthermore, a fine precipitate was formed, and this helped increase the strength of the alloy by forming more obstacles to the movement of dislocations. The ultimate tensile strength and yield strength increase as shown in Figure 3. The strengthening was due to the difficulty of the dislocations shearing or bypassing the particles. The degree of irregularity created by the rolling process in the lattices caused an increase in the mechanical properties of the mild carbon steel (Schindler et al. 2009; Cao et al. 2011). The strengthening effect of the mild carbon steel can be attributed to an interference with the motion of dislocation due to the presence of foreign particles of any other phase. However, from the bar, it can be seen that ductility reduces with increased cold rolling. The ductility follows an inverse relationship with the strength, as expected. The elongation of the mild carbon steel decreased gradually with increased rolling (Maklakova et al. 2015). Figures 4 and 5 show the microstructure analysis of as-received mild carbon steel and the microstructure of annealed mild carbon steel, respectively. It was revealed from the analysis that the optical micrograph of mild carbon steel in the received sample shows a coarse microstructure with large grain boundaries. It also exhibits a pile-up or high dislocation density in between grain boundaries and precipitates. However, the optical micrograph of annealed, rolled, mild carbon steel shows there is a serious transformation. The grain boundaries could no longer be seen vividly; the ferrite has precipitated with the pearlite as well, forming a grey color instead of clear white and black. The implication is that the longer or coarser the grain size, the softer the material as suggested by Rajput (2004) and Seyed (2010).

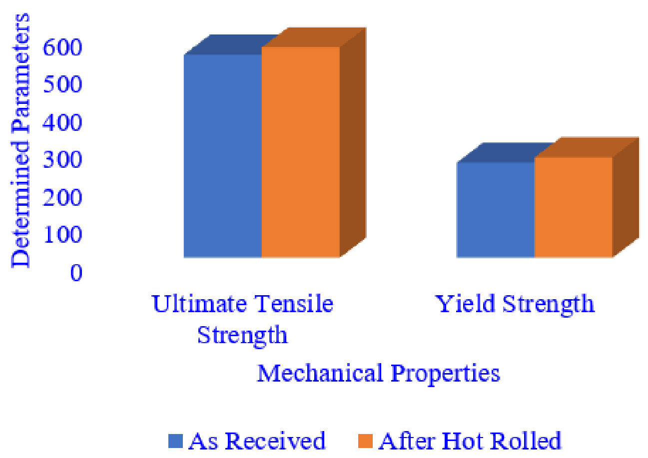

FIGURE 3. Evaluation of the yield strength and ultimate yield strength of rolled milled Al-6061 alloy

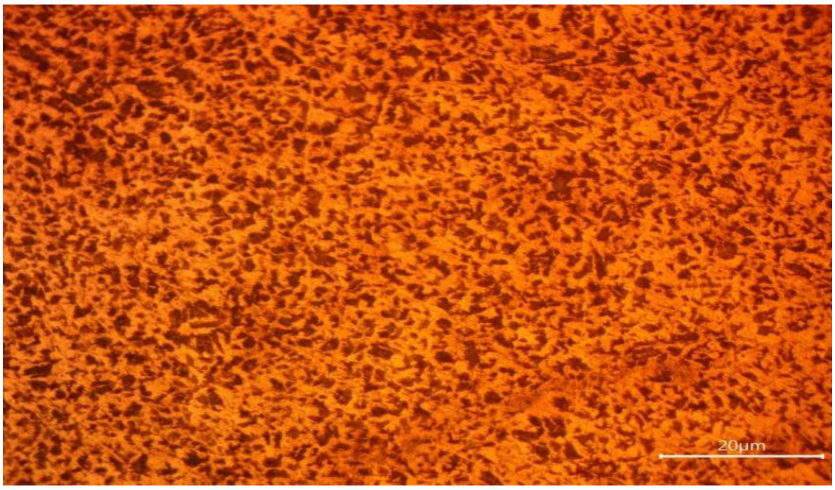

FIGURE 4. Microstructure of as received mild carbon steel

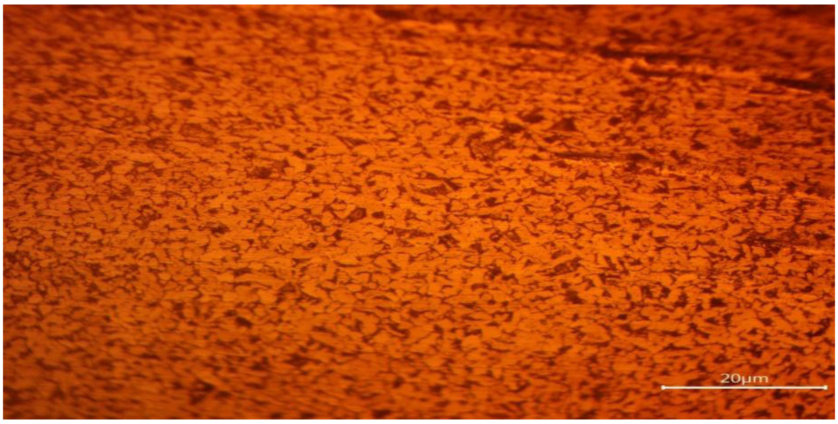

FIGURE 5. Microstructure of annealed rolled mild carbon steel

CONCLUSION

The results of the performance test evaluation showed a variation in alloy ductility, hardness, and strength. The ultimate yield strength of the annealed rolled mild carbon steel increased from 535.88 MPa to 540.05 MPa after hot working, as did the yield strength of the material, which increased from 250.85 MPa to 258.85 MPa. Also, there was an increase in the hardness and a decrease in the ductility of the rolled material. It was revealed from the analysis that the optical micrograph of the as-received sample shows a coarse microstructure with large grain boundaries. It also exhibits a pile-up or high dislocation density between the grain boundary and precipitates. However, the optical micrograph of annealed, rolled carbon steel shows there is a serious transformation. The grain boundaries could no longer be seen vividly; the ferrite has precipitated with the pearlite as well, forming a grey color instead of clear white and black. The largest grain size the implication is that the longer or coarser the grain size, the softer the material.

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DECLARATION OF COMPETING INTEREST

None

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