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Comparative Studies on Additive and Subtractive Manufacturing in Nigeria Case Study: Helical Gear in a Juice Extractor

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Authors' contributions

This work was carried out in collaboration among all authors. Author CFN designed and managed the analyses of the study. Authors AOF and AAO performed the statistical analysis, wrote the protocol, literature searches and wrote the first draft of the manuscript. Authors CFN, AEA and VCTU developed the gears using additive method while author OS developed the gears using subtractive method. Author WBA supervised the study. All authors read and approved the final manuscript.

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ABSTRACT

All over the world, additive and subtractive manufacturing are the two basic manufacturing methods used for the development of engineering goods and products. In most cases, the method adopted by the manufacturers usually depends on its cost-effectiveness. However, most of the manufacturing industries in Nigeria have little or no information on the relative advantages and disadvantages of the two methods. This had led to many industries adopting one particular method hook, line and sinker without considering the merits that would be offered by the alternative manufacturing method. This paper, therefore, compared the two methods of manufacturing by carrying out reverse engineering of worn-out helical gears (components of a juice extractor) developed using additive and subtractive manufacturing techniques. The parts of the equipment

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were developed using a lathe, milling and deburring machines to carry out the drilling, turning, grinding, milling and deburring for subtractive manufacturing and 3-D printing machine for additive method. Two gears A and B were developed by both subtractive and additive methods using the dimension of two old gears, which serve as the basis for determining the variation of the nomenclatures of the developed gears from the standard. The time used for product development, cost of production and the energy expended during the production of the two gears using additive and subtractive manufacturing methods were also determined using appropriate methods.

The study also showed that it is less expensive to produce both gears A and B using the additive method than the subtractive method. Similarly, in term of energy used, less energy was used during fabrication of the gears using additive method than subtractive method but in general, when you want to print a whole component at once the 3D printer volume could be a major constraint.

Hence, the adaptation of additive manufacturing method as a whole or part with the existing subtractive method will help to improve manufacturing industries in Nigeria.

Keywords: 3D printer; energy; production cost; gears; subtractive and additive methods.

1. INTRODUCTION

Global competition in the manufacturing field, cost-saving and new product design have resulted in the invention of a new manufacturing method to improve industrial processes. Before the industrial revolution of the 18th century that came with great innovations like spinning jenny, modern steam engine and so forth, hand tools were painstakingly used for the production of simple goods needed [1]. When people hear the word "machining" they generally think of the many processes that have this common theme, controlled material removal using shear as the primary method. These are today collectively known as subtractive manufacturing, in which, one starts with a single block of solid material larger than the final size of desired object and portions of the material are removed until the desired shape is reached [2]. These include most of the machining processes such as milling, grinding, turning, drilling and laser cutting. Nowadays, subtractive manufacturing is carried out by computer numerical control (CNC), in which computers are used to control the movement and operation of the mills, lathes, and other cutting machines. To perform these operations, relative motion is required between the tool and the work. This relative motion is achieved in most machining operations using a primary motion, called "cutting speed" and a secondary motion called “feed”. The shape of the tool and its penetration into the work surface, combined with these motions, produce the desired shape of the resulting work surface. Subtractive manufacturing allows you to design, prototype, and manufacture end-use materials. It is an appropriate choice for parts used for small and large volume production runs, to obtain specific finishes, or to obtain specific mechanical properties. On the contrast, additive manufacturing technique is a process of "joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer” [3]. Firstly, a 3D solid model of a part is built and converted into a standard additive manufacturing file format and then sent to an additive manufacturing machine before the part is finally built layer by layer [4]. This technology is now used in prototyping and distributed manufacturing with applications in architecture, construction, industrial design, automotive design, aerospace, military, engineering, agriculture, etc. It has also become popular in areas such as dental and medical technology, fashion, footwear, jewellery, eyewear and many more. Interestingly, even food is being printed nowadays [5,2]. Apart from these, there are also 3D digitizers, 3D sensors and 3D scanners, the possibilities are almost endless. But then, the cost of producing large volumes of goods through 3D printing is not always economical a result of the print volume of the printer and type of materials (filament) used. It can also be inexpensive to produce low volumes of goods when economies of scales are not required. Each manufacturing method has its advantages over the other. While additive manufacturing method can produce very intricate prototype designs that are impossible to replicate by the subtractive method, it is limited by the strength and product selection [6]. Nevertheless, 3D printing, which is one of the most significant industrial developments of this decade [7] had evolved from simple prototyping to fully integrated utilization in direct manufacturing as a result of its diverse applications. Despite the accelerated advancement, both in academic research and industrial applications that 3D printing technology has witnessed in diverse areas of human endeavour especially in advanced countries; the technology is relatively at its infant stage in Nigeria. Since the introduction of additive manufacturing methods globally (more than 30 years ago), very few Universities, research institutes and private enterprises are researching and using the technology in Nigeria [8,9]. The same trend was observed in the manufacturing industries as only a few industries in Nigeria make use of additive manufacturing method. With natural resources becoming more and more expensive, sustainability is becoming increasingly important to manufacturers in Nigeria. Thus, many manufacturers are yearning to adopt additive manufacturing method in their production processes but are limited by inadequate technical personnel to operate 3D printers, high cost of importing 3D printing which is unaffordable by most small and medium scale manufacturing industries in Nigeria and most importantly, lack of the basic information about additive manufacturing in relation to subtractive method of manufacturing. This is essential as it will guide and inform manufacturers on the merits and demerits of the two methods. They may then decide to adopt the new method wholly or partially as an integrated method that comprises the two manufacturing methods. From the foregoing, it can be seen that there is an urgent need for a radical restructuring of the manufacturing industry in Nigeria. And the foremost problem to tackle is the non-availability of the basic information about the merits and demerits of using the two methods. This paper, therefore, takes a critical look at the merits and demerits of the two manufacturing techniques by developing the component part (gear) of a juicer extractor using the two methods and compare the methods in terms of deviation of developed products from standard, cost of production, energy expended in production with respect to the production time used for the two methods with the aim of developing the best manufacturing techniques to produce cost-effective and quality products.

2. METHODOLOGY

2.1 Development of the Component Parts (Worn-out Gears)

The two gears were fabricated with due consideration to different gear nomenclatures that are used to described standard gears as shown in Fig. 1. Plate 1 shows the two gears A and B which are parts of a Green Star Tribest GS-3000 Deluxe HD Twin Gear Juice Extractor used at homes. The smaller gear, A is directly connected to a shaft which mesh with the bigger

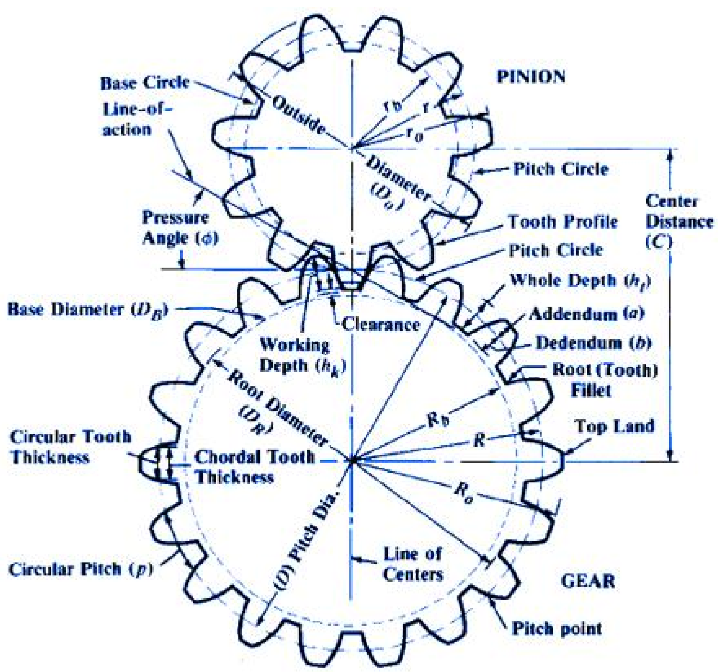

Fig. 1. Gear nomenclature

Source: https://www.engineersedge.com/gear_formula.htm

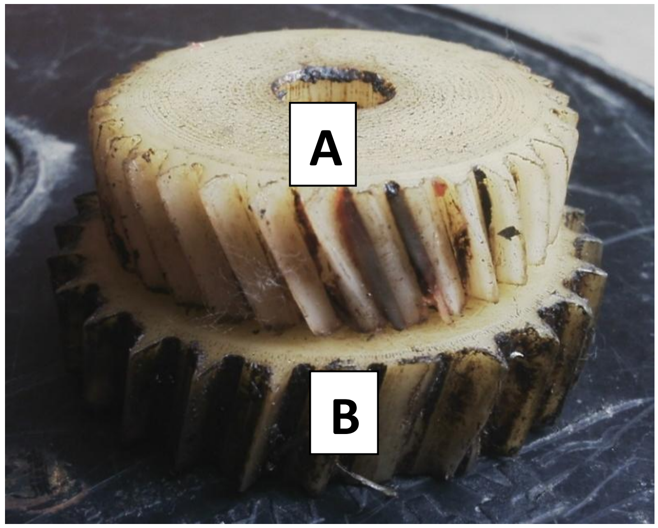

Plate 1. Worn out gears from green star tribest GS-3000 deluxe HD twin juicer to be replicated

gear, B, causing a reduction in speed of gear A. Motion is then transferred from gear A to gear B which also causes speed reduction to the twin gear that protrude out of gear B. Prior to the development of the parts, the dimensions of the gears were taken for both methods (subtractive and additive) using vernier calliper and engineering protractor to determine the diameter, thickness, pitch and helical angle of the gears. The gears are not completely worn-out. The tooth profile and pitch circle which are the affected parts of the old gears were obtained by measuring the centre distance between the gears and determined by the difference diameter with known base diameters.

2.1.1 Subtractive method used for product development

To develop the gears by subtractive method, firstly a 50 mm diameter was cut from a 1ft long solid Teflon Propylene material (High Density). This material was then faced, drilled, turned and parted off on an NH26 centre lathe machine to obtain 48 mm and 60 mm diameters circular solid gear without teeth for gears A and B respectively. Thereafter, the gears teeth were cut on a Universal Milling Machine (Knee Type) model U1 using a gear cutter Module 2 for gear A and Module 3 for gear B respectively. The two gears A and B are shown in Plate 2.

2.1.2 Additive method used for product development

To develop the gears by additive method, a Guider IIs 3D Printer with a single extruder, which has been purchased by Prototype Equipment and Specification Division of the Federal Institute of Industrial Research, Oshodi, Lagos was used to print the gear using a blue coloured, 1.75 mm diameter PLA (Polylactic Acid) filament. The 3D printing process involved in developing the product started with the conversion of the Autodesk Inventor drawing file to G-Code file that can be read by a 3D printer. Firstly, the drawing was stored in the STL file and then moved to the flash print slicer software (Plate 3), which converts it to .3 gx format recognized by the printer. Before uploading the drawing in this format to the printer, the layer height of 0.18 mm, infill of 100%, extruder speed of 60 mm/sec, extruder and platform temperatures of 220ºC and 50ºC respectively, were set for the two sizes of gears as shown in Plate 4. The extrusion temperature determines the flow rate of the filament unto the print bed where products are printed. The estimated time and the quantity of filament used are shown in Plate 5 while the produced gears A and B using this method are shown in Plate 6.

2.2 Time Determination

The time taken to fabricate the two gears using the subtractive method were recorded using a digital stopwatch while the time taken for additive was pre-determined by the flash print slicer software.

The total time taken for the subtractive method was estimated using equation (1)

$$\text{Total time taken} = \text{Measuring Time} + \text{Machining Time} + \text{Milling Time} + \text{Deburring Time} \quad (1)$$

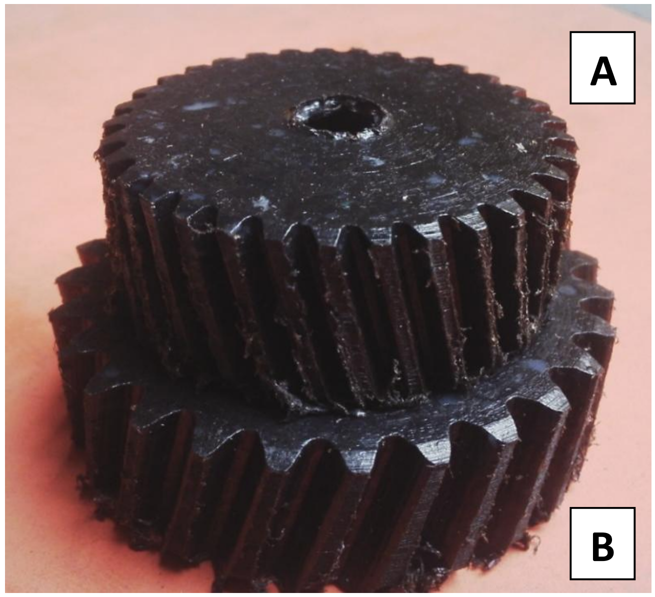

Plate 2. Replicated gears using subtractive method

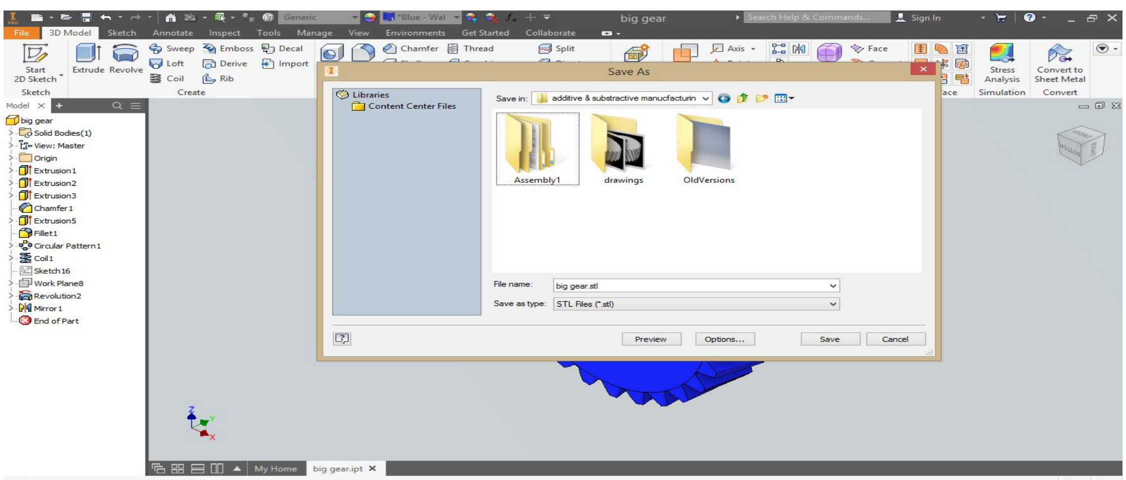

Plate 3. Conversion of drawing to STL file in autodesk inventor

Note that the measuring time is the sum of the time taken to sketch the drawing and the time used for measurement before machining commences. The total time for the additive method was estimated using equation (2)

$$\text{Total time taken} = \text{Measuring Time} + \text{Drawing Time} + \text{Printing Time} \quad (2)$$

2.3 Cost Determination

The cost of fabricating the two gears by both additive and subtractive methods were calculated using equation (3),

$$\text{Total Cost (N)} = \text{Cost of Electricity Consumed} + \text{Cost of Materials Used} + \text{Cost of Labour} \quad (3)$$

2.4 Determination of Energy Used

The energy used during the production of the gears using both additive and subtractive methods were calculated using equation (4).

$$\text{Total Energy Used} = \text{Human Energy Used} + \text{Electrical Energy Used} \quad (4)$$

The human energy was estimated according to [1] which reported that the minimum energy

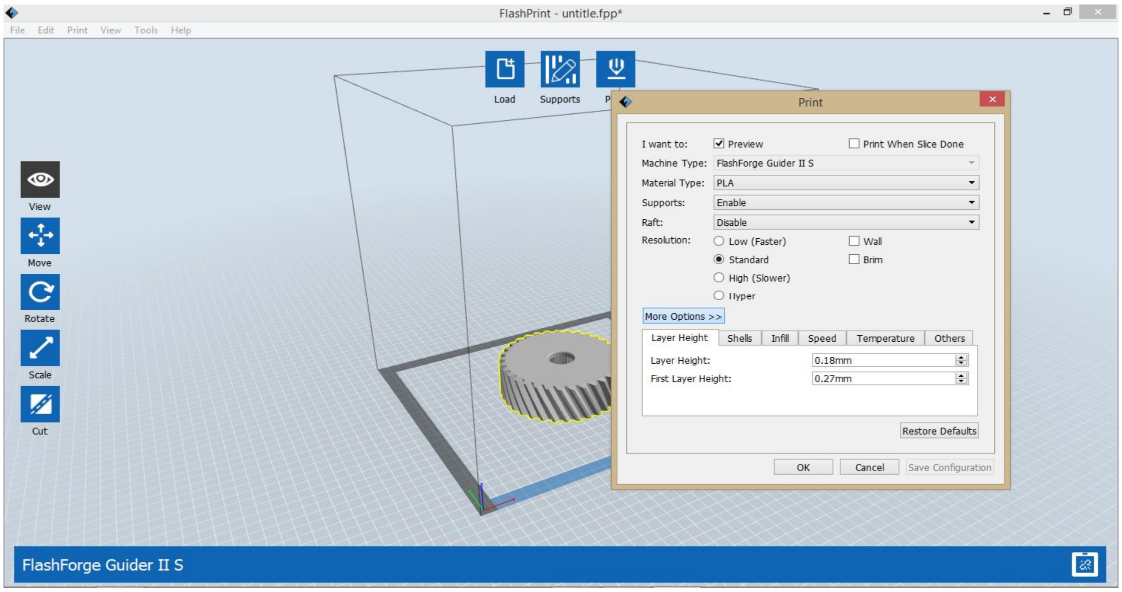

Plate 4. Flash print software (Flash forge guider iis slicer) showing setting mode for print

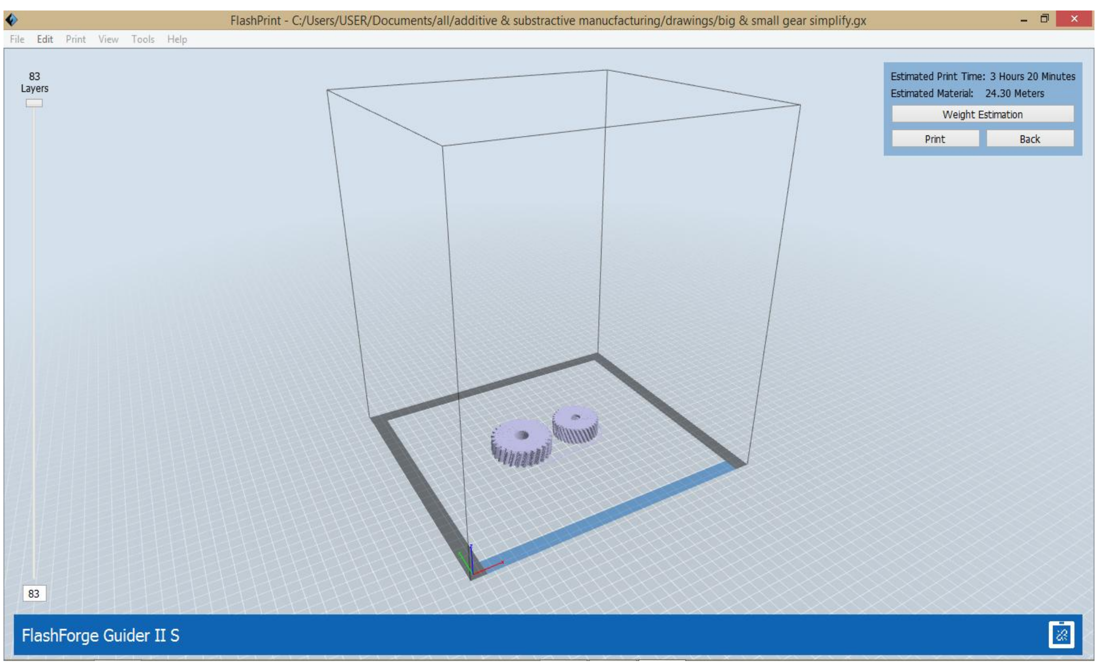

Plate 5. Image showing the estimated print time and quantity of filament to be used

requirement for Nigeria per day per human is 11,340KJ. Thus, the total human energy used to fabricate the two gears for both additive and subtractive methods were calculated based on the total time used by human effort for drawing and taken the measurement. The electrical energy was calculated from equation (5).

$$\text{Energy} = \text{Electrical Power} \times \text{Time} \qquad (5)$$

Where energy is in Joule, power is measured in Watt and time have taken is measured in Seconds

$$\text{Electric Power} = \text{IVT} \qquad (6)$$

Where I is current in ampere, V is voltage in volt and T is time taken.

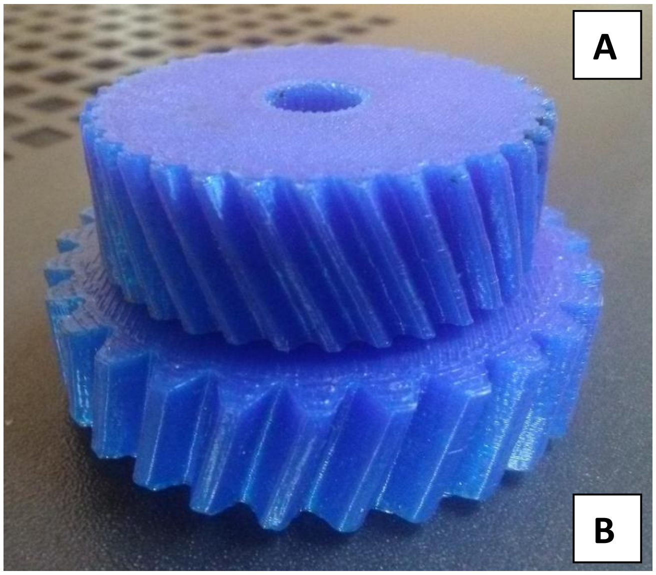

Plate 6. Replicated gears using additive method

3. RESULTS AND DISCUSSION

The graphs below show the variation in the gear nomenclatures of additive and subtractive from the old gear used as standard.

3.1 Outside Diameter

From Figs. 2 and 3, the outside diameter of the gear A using additive manufacturing is 2.00 mm smaller than standard gear. However, the subtractive method produced a gear A of 1.50 mm bigger than the standard gear. Similarly, the outside diameter of gear B produced by the additive method is 0.3 mm shorter than the standard gear while a gear B which is 2.00 mm wider than the standard was produced by the subtractive method.

3.2 Helix Angle

Also, from the figures, there was no difference between the helix angles of the standard gear and the gears manufactured by both the additive and subtractive methods. Similarly, there was no difference between the helix angle of the standard gear and that of gear B produced by additive manufacturing. However, using the subtractive method to produce gear B, gave a gear which is 2.00 mm wider in helix angle than the standard gear.

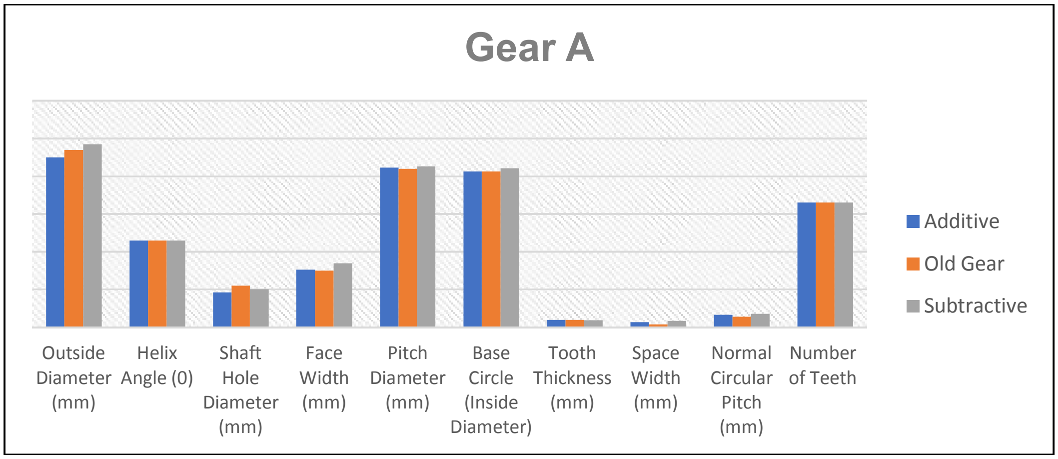

Fig. 2. Deviation in nomenclatures of Gear A from standard gear using additive and subtractive manufacturing methods

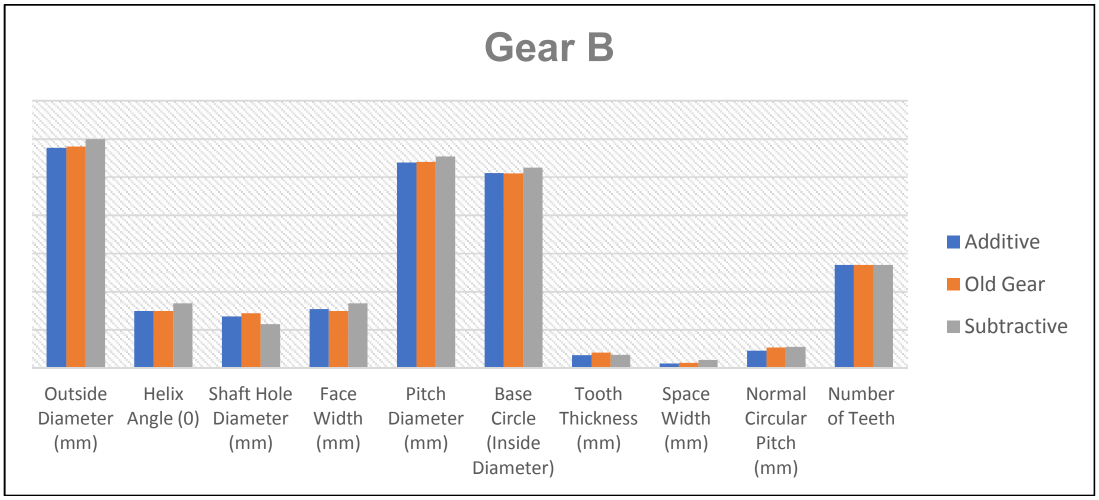

Fig. 3. Deviation in nomenclature of Gear B from standard gear using additive and subtractive manufacturing methods

3.3 Shaft Hole

The figures also showed that there were differences in the diameter of the shaft hole between the standard gear and those of gears A and B using the two manufacturing methods. For gear A, the shaft holes were 1.75 mm and 0.90 mm lesser in diameter than the standard using additive and subtractive methods respectively. However, for gear B, the shaft hole was 0.85 mm shorter than the standard and 0.80 mm wider for additive and subtractive methods respectively.

3.4 Face Width

The face width of gear A produced by both additive and subtractive methods were wider than the that of the standard gear by 0.20 mm and 2.00 mm for additive and subtractive methods respectively. Similar trends were observed in the production of gear B in comparison with the standard gear. The face width of gear B produced by additive and subtractive methods were 0.50 mm and 2.00 mm wider than that of the standard gear respectively.

3.5 Pitch Diameter

The figures also revealed that the pitch diameter of gear A produced using both methods were wider than that of the standard gear. The difference in width was however more pronounced in gear A produced by the subtractive method, which was 0.70 mm wider than that of the standard gear. On the contrary, the pitch diameter of gear B produced by the additive method was 0.15 mm shorter than the standard gear while gear B produced by the subtractive method was 1.5 mm wider in pitch diameter than the standard.

3.6 Base Circle

The circumference on the base circle on the gear A produced by additive was 0.05 mm wider than that of the standard gear. However, the circumference of the gear produced by subtractive was 0.75 mm shorter than the base circumference of the standard gear. The figures, however, showed that the production of gear B gave gears with 0.1 mm and 1.45 mm wider base circles for additive and subtractive methods respectively.

3.7 Tooth Thickness

There was no difference in the tooth thickness for gear A produced by the additive method and the standard gear. But the standard gear was 0.10 mm thicker than gear A produced by the subtractive method. However, the standard gear tooth thickness was 0.60 mm and 0.50 mm thicker than gears produced by additive and subtractive methods respectively.

3.8 Space Width

The space widths between the consecutive tooth on the gear A produced by additive and subtractive methods were wider than the

Table 1. Time used for the production of Gear A and B using subtractive methods

Gear type	Measuring & drawing time (Min)	Facing, drilling, turning & parting off time (Min)	Milling time (Min)	Deburring time (Min)	Total time (Min)
Gear A	180	60	110	35	385
Gear B	180	70	140	30	420

Table 2. Time used for the production of Gear A and B using additive method

Gear type	Human (Measuring & drawing time) min	Electrical (Printing time) min	Total time used min
Gear A	220	87	307
Gear B	232	113	345

standard gear by 0.50 mm and 0.90 mm respectively, However, to produce gear B, additive method produced a gear with a space width shorter by 0.20 mm while a gear with a space width 0.75 mm wider than the standard gear was produced by subtractive method.

3.9 Normal Circular Pitch

Following the same trend as that of the space width, wider normal circular pitches of 0.50 mm and 0.80 mm than the standard were obtained during the production of gear A using additive and subtractive methods respectively. However, the normal circular of gear B produced by the additive method was smaller than the standard while gear B produced by subtractive was 0.25 mm wider than the standard gear.

3.10 Number of Teeth

The graphs also showed that the total number of teeth on both gears A and B using the two manufacturing methods were 33 and 27 respectively. This was the total number of teeth on the old gears used as standards.

Generally, from the graphs, it can be deduced that there was less variance in the dimensions of gears A and B from the standard using additive than the subtractive method with pronouncing variation in dimensions observed in the smaller gear A. This was as a result of the difficulty involved in producing small scale products by subtractive method. For instance, not all materials are removed from small material during turning on the lathe machine to form the desired product because of the intrinsic process involved. Thus, the dimensions of small-sized gears A produced are not as close to the dimensions of the standard gears as big gears B. However, as the scale of the product increases, machining of parts become less intrinsic and the precision level of the developed product by the subtractive increase.

3.11 Production Time used for Gear Production

From Tables 1 and 2, the time of production for the subtractive method which includes the time expended in measuring, facing, drilling, turning, milling, deburring and parting off of material from the workpiece was 230 mins and 205 mins for gears A and B respectively. However, manufacturing the two gears using additive methods took shorter production time, with a production time of 87 mins and 113 mins for gears A and B respectively.

3.12 Cost of Producing Gear

As shown in Table 3, the cost of producing gear A was lesser than gear B for both additive and subtractive manufacturing methods. However, for both gear A and B, the additive manufacturing method is cost-efficient with a cost which is N1,500 and N1,000 lesser than the subtractive method for gear A and B respectively. The higher difference in cost in the production of gear A compared to B using additive was due to lesser PLA materials used in the production of gear A.

Table 3. Production cost for additive and subtractive methods

Gear type	Additive	Subtractive
	N	N
Gear A	5,300	6,800
Gear B	7,000	8,000

Table 4. Energy used during additive and subtractive methods

Gear type	Subtractive human energy	Subtractive electrical energy	Subtractive (Human + Electrical)	Additive human energy	Additive electrical energy	Additive (Human + Electrical)
	KJ	**KJ**	**KJ**	**KJ**	**KJ**	**KJ**
Gear A	1,423	323	1,746	1,739	9.21	1,748.21
Gear B	1,423	378	1,801	1,834	10.35	1,844.35

3.13 Energy Expended During Production

Table 4 shows the energy expended using the two manufacturing methods. There was much energy used in the production of the two gears using the subtractive method than the additive method. For both methods, the table showed that human energy was higher than electrical energy employed. For subtractive technique, much effort was used in carrying out activities such as measurement, drilling, facing milling and parting out than CAD drawing and gear measurement which are the major human effort used in additive manufacturing method apart from the effort used in filling the PLA material which can be considered insignificant. The table also showed that the wider the diameter of the gear, the higher the energy used for the production as more energy will be required to remove a large volume of material from the workpiece during the fabrication process. The table also revealed that the difference between the energy used for fabricating gear A and B using subtractive manufacturing is six times the difference the between the energy used for fabricating gear A and B using the additive method.

4. CONCLUSION

The comparative study showed that additive manufacturing method using 3D printing method though, less popular among manufacturers in Nigeria produced gears that are closer to the standard dimensions than the commonly used subtractive method. They are also less expensive and used lesser energy. Hence, the adaptation of additive manufacturing techniques as a whole or part with the existing subtractive method will help to improve gear manufacturing and as well as revolutionize the entire manufacturing industries in Nigeria.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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