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Research Article

Identification of Dry Sliding Wear Behaviour of PLA Parts Manufactured by Fused Deposition Modelling

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ABSTRACT

In this study, wear behavior of Poly Lactic Acid (PLA) parts manufactured by one of the additive manufacturing techniques Fused Deposition Modelling (FDM) is investigated and modelled via linear and non-linear identification. Transfer Function, Process Model and Nonlinear Autoregressive with Exogenous Input (NARX) model are used as modelling. Identified wear models are established according to wear tests conducted on Pin-on-disc test apparatus under constant load and constant sliding distance. Two different manufacturing orientations are chosen for the PLA pin specimens and wear tests are performed against steel and cast iron discs. Obtained results from the identified models are compared with the experimental results to select most efficient and reliable model structure.

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Introduction

Functionally used mechanical components are conventionally manufactured from metals and their alloys. Mechanical performances of these materials are remarkably improved over the years. However, parts manufactured from polymers show better performance in terms of lightweight and ease in production. Due to their good tribological properties, light weight and low cost polymers are widely used in many engineering applications such as journal bearings, seals, bushes, gears, electrical applications, etc. [1–6]. Due to adhesive transfer film that occurs during the friction polymeric materials show great wear resistance in dry sliding conditions [6]. The other advantage of the polymers is that they could be manufactured by using rapid prototyping techniques like Fused Deposition Modelling (FDM). FDM is one of the additive manufacturing processes that is cost effective and fast. Parts manufactured by this technique have lack of strength. In recent years, functional use in machine elements has come into use. For this reason, it is important to investigate the mechanical properties of these parts. Researches in the literature about wear characteristics of these parts are very limited. There are studies about wear behavior of polymers built by Fused Deposition Modelling [7–10]. These studies mostly focus on improving wear resistance of polymer by adding wear resistant materials as reinforcement such as Al2O3, SiC, Graphene etc.

Beside these experimental studies, there are studies investigating the influences of different process parameters on test specimens' wear behavior, which are manufactured by FDM. Sood et al. [11] have considered five process parameters to understand the effect on the wear behavior of the test specimens. Parameters are layer thickness, part build orientation, raster angle, raster width and air gap. ABS P400 is used as material. A statistically validated predictive equation is developed. Since process parameters have great impact on the responses in a nonlinear manner, artificial neural network (ANN) is used for the verification of the results. Mohamed et al. [12] have studied the effect of different production parameters of FDM on wear mechanism of manufactured prototypes by using definitive screening design and partial least squares regression. Layer thickness, air gap, raster angle, build orientation, road width and number of contours are taken as process parameters.

The studies on PLA (Poly Lactic Acid)'s wear behavior is very limited in the literature. Bustillos et al. [8] have studied the wear properties of PLA and PLA-Graphene composites. In mechanical engineering applications, ABS material is preferable than PLA as a plastic material, because PLA's glass transition temperature range is smaller than ABS. However, PLA is used frequently in Biomechanical applications due to its biodegradability [13–15].

In this work, wear mechanism of PLA parts manufactured by Fused Deposition Modelling (FDM) is investigated. Wear rates of the each test calculated and plotted against sliding distance. For the identification three different model structures were chosen, which are Transfer Function, Process Model and Nonlinear ARX model. Simulation results made by these models are compared with the experimental results.

Materials and Methods

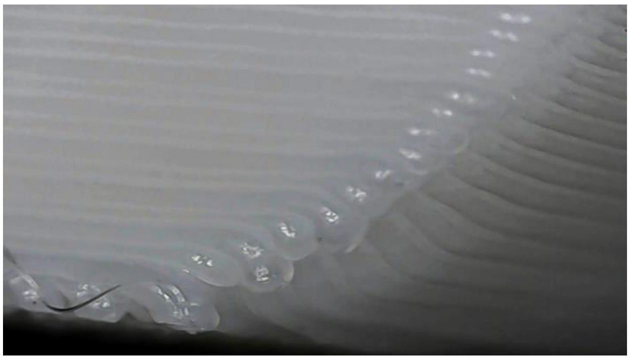
The solid model of the pin specimens is created in the three-dimensional (3D) modelling software SolidWorks and exported as a stereolithography (STL) file. The MakerBot Desktop software is used to slice the STL file vertically and horizontally by choosing two different directions, parallel and vertical to the build platform. These two files are used to produce vertical and horizontal oriented pin specimens. Pin specimens for wear tests are fabricated in the form of test bars by using 3bfab PLA filament and the MakerBot Replicator 2 desktop printer. As the manufacturing parameters, layer height is 0.1 mm, extruder temperature is 230 °C and infill ratio is 100%, are chosen. Manufacturing orientations are shown in Figure 1.

(a) (b)

Figure 1. (a) Vertical, (b) Horizontal oriented manufactured PLA pin specimen

For the vertically produced specimen (a), the FDM layers of the PLA material are in a parallel position to the build platform, while those produced horizontally (b) are in an upright position. Microscopic images of PLA layer lines are also shown in Figure 2.

(a)



(b)

Figure 2. Digital microscope images of PLA layer lines for FDM parts: (a) Vertical, (b) horizontal oriented pin specimens

Wear Tests

Coefficient of friction and the wear rate of 3D printed PLA specimens were evaluated for dry sliding conditions using pin on disc method at room temperature. Tests were conducted under the guidance of ASTM G99 standard [16]. Cast iron and steel has been chosen for the abrasive counter disc materials which have varying surface roughness and hardness. Specification of counter discs and 3D-printed PLA specimens are shown in Table 1 along with the wear test parameters.

For each the disc which is shown in Figure 3, surface roughness was measured three times and the arithmetic average of the roughness profile was calculated. Figure 4 shows surface textures for the counter discs. The graphs of surface roughness is also shown in Figure 5.

Table 1. Wear test parameters and specifications of pin specimens and counter discs.

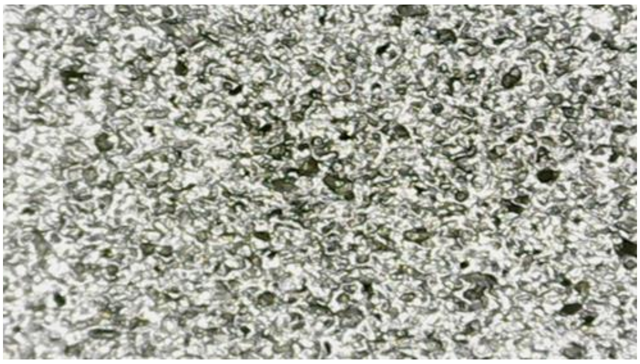
Parameters	Values
Steel disc material	AISI 1040
Steel disc diameter (mm)	100
Steel disc thickness (mm)	10
Steel disc hardness (HV)	211
Steel disc roughness (Ra)	3.2
Cast disc material	White Cast Iron
Cast disc diameter (mm)	100
Cast disc thickness (mm)	10
Cast disc hardness (HV)	526
Cast disc roughness (Ra)	6.2
Normal Force (N)	10
Sliding Distance (m)	500
Sliding Speed (m/s)	2×10^{-1}
Pin diameter (mm)	10
Pin length (mm)	30
Test Temperature (°C)	23

(a) (b)

Figure 3. Counter discs: (a) Cast iron, (b) Steel

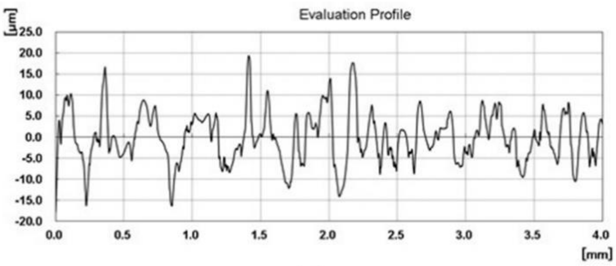
The load was applied to the specimen and the arm of the machine was balanced by a counterweight. The specimens were weighted before each experiment, on a sensitive balance with sensitivity of 1×10^{-4} g. Test apparatus where the tests are carried out are shown in Figure 6. During the test, the tangential frictional force was measured with a load cell and recorded by the computer. The wear tests were performed using a normal load of 10 N at a sliding speed of 22×10^{-2} ms^{-1} and the total sliding distance was 500 m. After each period of the test, the test machine was stopped, the samples were cleaned and weighted again to calculate the weight loss. All the weight measurements were done using an electronic weighing machine, AND GR 202, with an accuracy of 0.1 mg. For each test condition, at least three samples were tested to obtain the average.

(a)

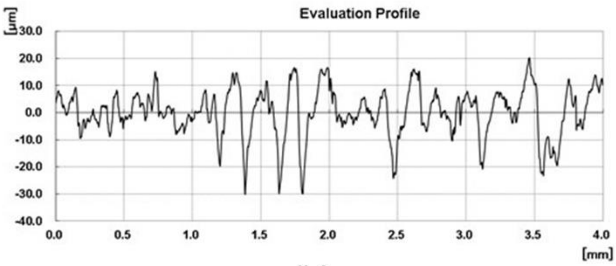


(b)

Figure 4. Digital microscope images of counter disc surfaces: (a) Cast iron, (b) Steel disc



(a)



(b)

Figure 5. Surface roughness: a) Cast iron disc, b) steel disc

Specific wear rate (K) was calculated using the following expression (1):

$$K = \frac{\Delta m}{\rho \cdot L \cdot F} \tag{1}$$

where Δm was the lost weight of a pin specimen in kg, ρ was the density in kg.m^{-3}, F was the load in N and L vas the sliding distance in meter.

Figure 6. Pin on disc test apparatus

Identification Procedure and Modelling

System identification uses statistical methods to build mathematical models of dynamical systems from measured data. Identification procedure was involved in four stages: Preparation, analysis, model structures preselection and identification.

For the identification process single input single output system was studied. The measured frictional force was chosen as input whereas calculated wear rate was the output for identification process.

Linear and nonlinear models which are Transfer Function model and Process model and NARX model were obtained by using MATLAB software. Transfer Function model which is described by the equation (2):

$$G(s) = \frac{K_p}{1+T_{p1}s} \tag{2}$$

Second model was Process model which is described by the equation (3):

$$G(s) = \frac{K_p}{1+T_{p1}s} e^{-T_d s} \tag{3}$$

For both models, $G(s)$ is the transfer function of the wear process, K_p is the steady-state gain, T_{p1} is a time constant, s is the Laplace operator and T_d is the time delay in Equation (3). To determine the model parameters in linear models the Levenberg–Marquardt optimization algorithm was used.

The third model structure was chosen as nonlinear autoregressive exogenous (NARX) model. Sigmoid network with one unit in a hidden layer was used to model wear behavior. The sigmoid function is given with Equation (4):

$$f(x) = \frac{1}{1+e^{-x}} \tag{4}$$

Nonlinear sigmoid function curve is given in Figure 7. Levenberg-Marquardt algorithm was used as optimization of the network weights. NARX model structures also given in Figure 8.

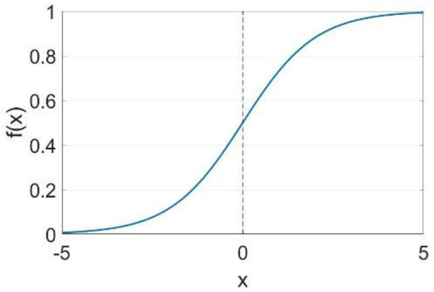


Figure 7. Sigmoid function

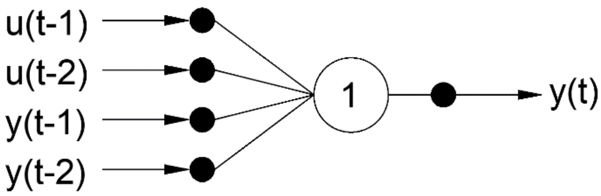


Figure 8. Nonlinear ARX model structure of the wear process

Results and Discussion

Manufacturing orientation of FDM parts play important role in wear mechanism as seen in Figure 9. Although, friction of coefficient values which is shown in Figure 10 seems to be higher in horizontal oriented pins, weight loss amounts are much less than the vertical oriented pins. This is because, layers perpendicular to the counter surface tend to split up due to nature of layer by layer manufacturing process. Despite the fact that cast iron has rougher surface than steel discs, there is a slight difference between friction coefficient values against cast iron and steel discs which can be observed in Figure 10. This result can be explained by the self-lubricating mechanism of cast iron due to its carbon content.

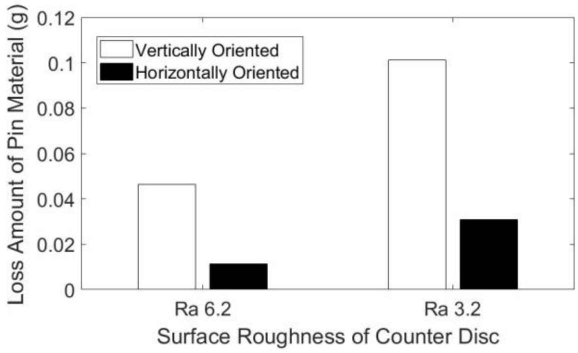


Figure 9. The graph of weight loss of pins

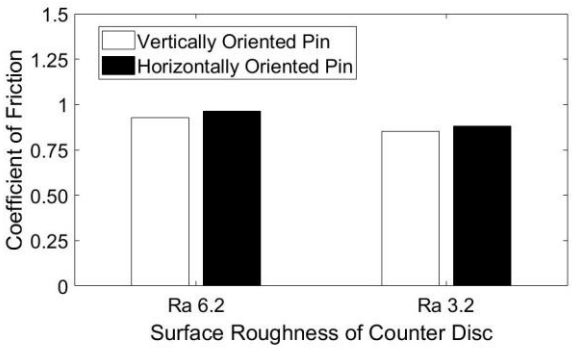


Figure 10. The graph of frictional force

In Figure 9, weight fraction of the vertical and horizontal oriented specimens against cast iron and steel discs could be seen. Revealed results indicate that surface roughness doesn't play an important role when it comes to weight loss.

Figure 11 to Figure 14 shows the typical variation of the friction force for each experiment.

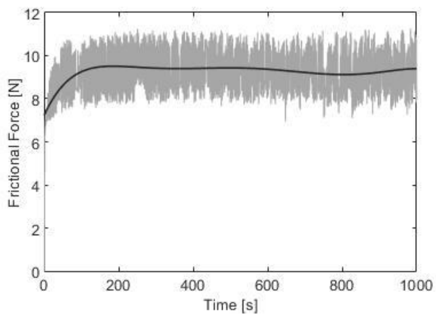


Figure 11. Vertical Orientation- Cast iron as counter material (Ra 6.2)

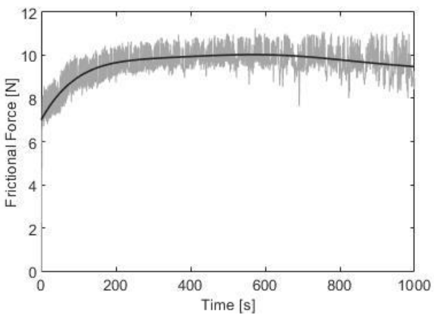


Figure 12. Horizontal Orientation- Cast iron as counter material (Ra 6.2)

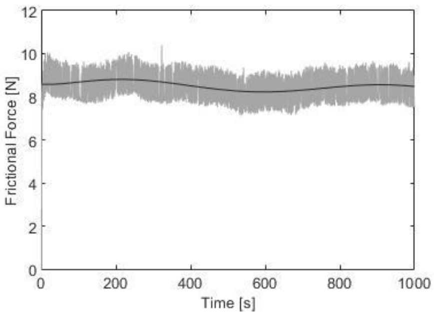


Figure 13. Vertical Orientation- Steel as counter material (Ra 3.2)

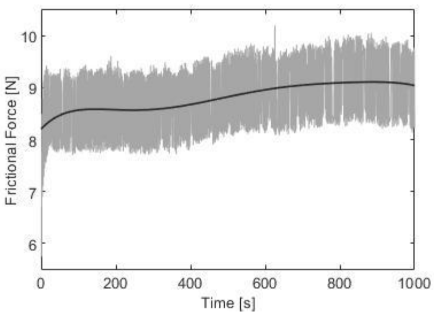


Figure 14. Horizontal Orientation- Steel as counter material (Ra 3.2)

The wear rate calculated for each experiment and the identified model simulations are shown in Figures 15 to 18. As it is shown in the figures, simulations with NARX models show better performance to predict the wear rate than transfer function and process models.

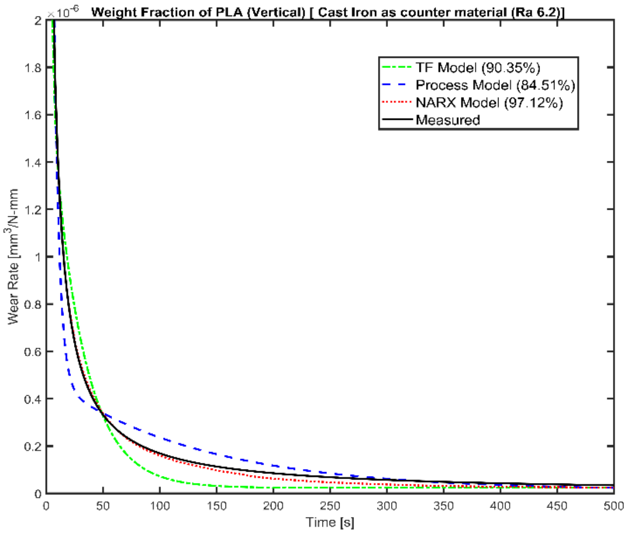


Figure 15. Weight fraction against cast iron (vertical orientation)

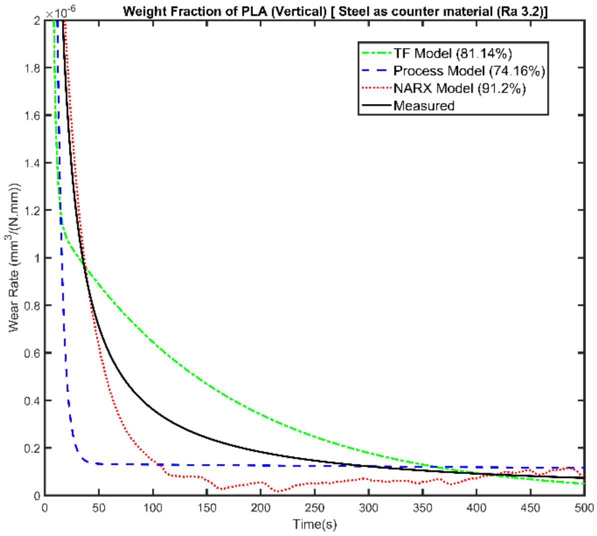


Figure 16. Weight fraction against steel (vertical orientation)

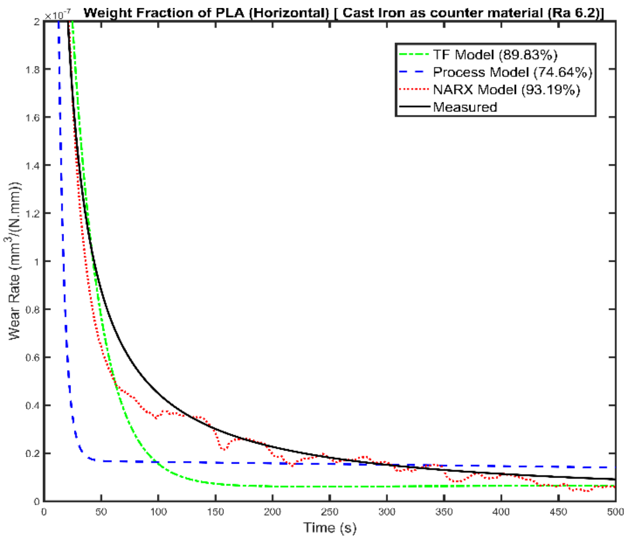


Figure 17. Weight fraction against cast iron (horizontal orientation)

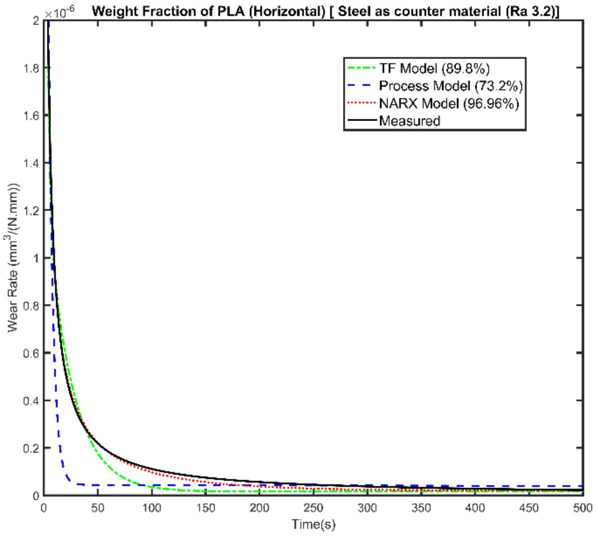


Figure 18. Weight fraction against steel (horizontal orientation)

Identification results and identified models are given in Table 2. NARX models fit to estimation data between 91.2% and 97.12%. The NARX model of vertical manufactured pin specimen against cast-iron friction pair fits 97.12% to estimation data which is the best fit value of the modelling results. Transfer function and process models show second and third better performance (81.14–90.35% and 73.2-84.51%) respectively.

Table 2. Modelling results and coefficient of friction

Disk Material / Surface finishing (Ra)	Pin Production Method	Transfer Function Models $G(s) = \frac{K_p}{1 + T_{p1} \times s}$ (Fit to estimation data %)	Process Models $G(s) = \frac{K_p}{1 + T_{p1} \times s} \times e^{-\tau_d \times s}$ (Fit to estimation data %)	Nonlinear ARX models (Fit to estimation data %)	Coefficient of friction
Cast-iron **Ra=6.2**	Vertical	$G_0(s) = \frac{-2.6653 \times 10^{-9}}{1 + 27.334s}$ (90.35%)	$G_0(s) = \frac{5.8286 \times 10^{-10}}{1 + 10000s} e^{-0.01s}$ (84.51%)	Sigmoid Network with 1 neuron (97.12%)	0.926319
Cast-iron **Ra=6.2**	Horizontal	$G_0(s) = \frac{-2.4628 \times 10^{-9}}{1 + 10000s}$ (89.93%)	$G_0(s) = \frac{-1.3345 \times 10^{-9}}{1 + 4724.6s} e^{-0.014s}$ (74.64%)	Sigmoid Network with 1 neuron (93.19%)	0.9619
Steel **Ra=3.2**	Vertical	$G_0(s) = \frac{8.3894 \times 10^{-9}}{1 + 4452.6s}$ (81.14%)	$G_0(s) = \frac{3.9717 \times 10^{-9}}{1 + 2446.8s} e^{-0.034s}$ (74.16%)	Sigmoid Network with 1 neuron (91.2%)	0.850786
Steel **Ra=3.2**	Horizontal	$G_0(s) = \frac{5.8368 \times 10^{-9}}{1 + 10000s}$ (89.8%)	$G_0(s) = \frac{2.5272 \times 10^{-9}}{1 + 1906s} e^{-0.104s}$ (73.2%)	Sigmoid Network with 1 neuron (96.96%)	0.88188

Conclusions

In this study, relationship between wear resistance of PLA specimens manufactured by FDM process and manufacturing orientations which are vertical and horizontal positions were investigated. Standard pin-on-disc wear tests conducted on cast iron disc and steel disc with Ra 6.2 and Ra 3.2 surface roughness values respectively. Then, system identification procedures were implemented for linear and nonlinear modelling of wear rates under dry sliding test conditions. MATLAB Identification Toolbox is used for the identification procedure. Wear rates versus time of the each tests were plotted and process model, transfer function model and NARX model structures were chosen to identify wear rates. Model parameters were identified to develop an appropriate model for wear loss estimation and simulations. Following conclusions can be listed from this study:

- Since the cast iron counter discs have higher surface roughness (Ra 6.2) which is more than steel discs (Ra 3.2), material loss for the cast iron discs expected to be higher than steel discs. However results show the opposite, weight loss against cast iron disc in vertically and horizontally oriented specimens are 0.042 gr and 0.01 gr respectively and against steel disc 0.1 gr and 0.03 gr respectively. These results could be explained with the filled PLA particles on cast iron porous surface which decreases the loss amount of pin material.

- Effect of manufacturing orientation to the weight fraction could be observed in the experimental results. While loss amounts of material are 0.042 gr and 0.1 gr in vertical oriented pins against Ra 6.2 and Ra 3.2 counter discs respectively. In horizontal oriented ones these values decreases to 0.01 gr and 0.03 gr.

- In vertically oriented pins, loss amount of weight is much higher than horizontally oriented ones. It emerges that layer's direction relative to the counter surface plays important role in wear mechanism. Layers perpendicular to the counter surface tend to damage and shear off more than layers parallel to the counter surface.

- Although weight fraction is much higher in vertically oriented specimens than horizontally oriented ones, it couldn't be concluded as such with friction of coefficient values. In the results, friction coefficient values of vertically oriented specimens were slightly less than horizontally oriented ones. While horizontal oriented pins against cast iron and steel discs have friction coefficient values of 0.9619 and 0.88188 respectively, ones with vertical orientation have friction coefficient values of 0.926319 and 0.850786 respectively. This is because contacting surface area of pins with counter surface is larger in horizontally oriented specimens due to parallel layers upon the counter surfaces.

- It is expected that friction coefficient values of pins against cast iron would be higher than pins against steel when surface roughness values taken into the consideration. Nevertheless, friction coefficient values in vertically and horizontally orientations are 0.926319 and 0.9619 respectively. These are slightly higher than values of pins against steel discs which are 0.850786 and 0.88188. The difference is minor as it seen. It could be explained with carbon content and the porous structure of cast iron. Porous structure give rise to fill of PLA particles into these pores. These particles on the disc surface and the lubricating effect of carbon element makes a positive impact on friction coefficient.

- The results of simulations showed adequate agreement with the experiments. Wear loss of friction material could be predicted at any sliding distance and time without conducting further experiments by using these simulations.

- NARX model shows better performance to predict wear weight fraction than transfer function and process models.

- The best fit with the experimental results were obtained in the case of vertical oriented pins and Ra 6.2 surface roughness. In this case, NARX model, Process model and transfer function model coincided with experimental results by 97.12%, 84.51% and 95.30% respectively.

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