MATERIALE PLASTICE
https://revmaterialeplastice.ro
https://doi.org/10.37358/Mat.Plast.1964

Comparative Examination of Friction Between Additive Manufactured Plastics and Steel Surface

PATRICIA ISABELA BRAILEANU[1], ANDREI CALIN[1], TIBERIU GABRIEL DOBRESCU[2*], NICOLETA-ELISABETA PASCU[2]

[1]Politehnica University of Bucharest, Faculty of Mechanical Engineering and Mechatronics, Department of Machine Elements and Tribology, 313 Splaiul Independentei, 060042, Bucharest, Romania

[2] Politehnica University of Bucharest, Faculty of Industrial Engineering and Robotics, Department of Robots and Production Systems, 313 Splaiul Independentei, 060042, Bucharest, Romania

Abstract: *Nowadays, the increasing use of plastic materials in friction and wear applications, particularly in industrial robotic grippers, is a growing trend in modern industry. Plastics are replacing traditional materials like metals and composites due to their unique properties and significant advantages. Plastic materials used in industrial robotic grippers offer several advantages, such as their low friction coefficient, enabling smooth and precise movement of the gripper and minimizing the risk of damaging the objects being manipulated. This paper presents a comparative study and analysis of the friction coefficient between various plastic materials and the C45 alloy steel, a superior alloy used in industrial applications. The investigated materials include PETG, PLA, PLA with aluminum, ABS, two types of TPU, and two types of UV-sensitive resins. This study aims to evaluate the friction performance of these materials in order to identify the most suitable options for friction and wear applications, such as industrial robotic grippers. To achieve this, dry kinetic friction tests were conducted between 3D printed plastic material samples manufactured by using FDM and SLA technologies, and the C45 alloy steel on the CETR UMT-2 tribometer. The friction coefficient was measured by recording the force required for displacement in two horizontal directions.*

Keywords: *friction study, COF, plastic materials, alloy steel, additive manufacturing*

1. Introduction

The use of plastic materials in friction and wear applications, such as industrial robotic grippers, is becoming increasingly prevalent in modern industry. Plastics have gradually replaced traditional materials like metals or composites in a wide range of applications due to their unique properties and significant advantages they offer. Industrial robotic grippers are essential mechanical devices in automating industrial processes, responsible for handling and moving objects in an industrial environment, playing a crucial role in improving efficiency and productivity. An important feature of robotic grippers is their ability to ensure a secure and stable grip on objects, regardless of their shape, size, or weight, while also considering the fragility of the objects being handled in the industrial environment to prevent damage during manipulation [1].

Plastic materials used in industrial robotic grippers provide several significant advantages [2]. One of the most notable aspects is the low friction coefficient of plastics, allowing smooth and precise movement of the gripper, minimizing the risk of damaging the manipulated objects. Additionally, plastics can be designed to have high wear resistance based on the working conditions of the industrial equipment, thereby extending the lifespan of the gripper components. The flexibility and versatility of plastic materials are other characteristics that make them an ideal choice for such applications. Plastics can be molded and manufactured in a wide range of shapes, sizes, and textures to fit the exact specifications and requirements of the specific application. This adaptability allows the creation of customized gripping surfaces with optimal anti - slip and adhesion properties and the ability to select

**email: tibidobrescu@yahoo.com*

plastics that are resistant to chemicals, high or low temperatures, and aggressive environmental conditions can be another advantage of these materials. This additional resistance contributes to the reliability and durability of the system, ensuring optimal operation in various industrial environments.

Also, the use of additive manufacturing for gripper components, such as the gripping jaws or coating parts with plastic materials, represents an innovative and efficient solution for their production. Using additive manufacturing in gripping jaws manufacturing allows to design and 3D print these components as a single unified piece, eliminating the need for subsequent assembly or welding, depending on the chosen 3D printing technology and the geometric shape. This can lead to less production time and costs, as well as an increase in the efficiency and quality of the gripper. Additive manufacturing can use also advanced plastic or composite materials that offer excellent properties of strength, durability, and adhesion, such as materials with anti-slip properties or low friction coefficients that can be used to ensure a secure and stable grip on manipulated objects. The 3D printing process also allows for the strategic integration of internal structures and wiring channels into the gripping jaws design, facilitating internal routing for power cables, sensors, or other electronic components, contributing to efficient installation and better protection of these elements. Moreover, this internal integration can reduce the weight of the final component, optimizing the performance and maneuverability of the gripper [3]. Such an approach highlights the ability to rapidly prototype and iterate in the additive manufacturing process multiple design variations, which can be tested and optimized in a short time, without incurring significant costs for changes or revisions. This allows to increase flexibility and adaptability in the development of industrial grippers, by facilitating the innovation and refinement process of the products. Thus, the use of plastic materials in industrial robotic gripper applications, combined with additive manufacturing, brings multiple advantages, such as cost and time reduction in production, improvement in performance and quality, strategic integration of components, and custom prototyping [4]. This technology offers an innovative and efficient solution to produce customized components tailored for specific needs in industrial robotic grippers.

2. Materials and methods

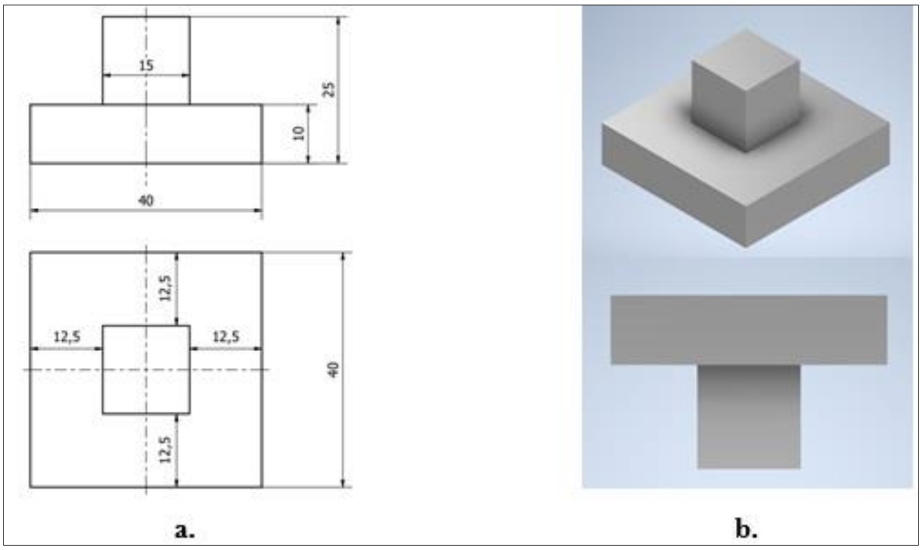


Figure 1. The sample design, a. Sample dimensions; b. The CAD sample used in this study

This section aims to describe each stage of this study along with the methods used in testing the samples, from the designing phase of the samples and the various software applications used, their manufacturing, and up to their experimental testing.

2.1. Samples design

The design of the additive manufactured samples was built by using the Autodesk Inventor Professional software. A parallelepiped shape was designed with a length and width of 40 mm and a height of 10 mm. On the surface of the parallelepiped, a *leg* was designed to be used later for securing the sample in a special fixture on the testing equipment. Figure 1 illustrates all the dimensions used in the subsequent construction of the samples. The file was later exported in *STL* format to be imported and processed in the 3D printer slicing software [4, 20, 21].

2.2. The materials used in sample manufacturing

A wide range of plastic materials with different mechanical properties and characteristics was chosen, so that the test results can help in selecting the appropriate material for the industrial gripper jaws, depending on the objects that must be manipulated. Thus, the following plastic materials were used in this study:

a. PETG (Polyethylene Terephthalate Glycol) is an extremely durable thermoplastic material with remarkable impact and abrasion resistance, being distinguished by its superior optical transparency and providing excellent clarity in applications where visibility is important. This material exhibits chemical resistance, capable of withstanding a variety of chemicals including diluted acids and solvents [5].

One significant advantage of PETG is the facility with which is processed, being compatible with various processing technologies such as casting, extrusion, and 3D printing. This allows to produce components and objects with complex shapes and fine details. Additionally, PETG has moderate thermal resistance, maintaining dimensional stability and resisting thermal deformation over a wide range of temperatures, it also stands out for its hygienic and safety characteristics, non-toxic and non-emitting material, approved for food contact and used in various medical applications, including medical equipment and pharmaceutical packaging [6].

Due to these remarkable properties, PETG finds applications in diverse industries, including packaging, consumer goods manufacturing, medical equipment, industrial components, and more. PETG can be a suitable solution for the industrial gripper jaws that come into contact with food or other products that should not be contaminated, such as in the case of pneumatic grippers. In Table 1 is shown the main PETG material properties ranges [7].

b. PLA (Polylactic Acid) is a biodegradable polymer derived from renewable sources such as corn starch or sugarcane. Its main characteristic is biodegradability, as it can naturally decompose in the environment through biological processes, making it an eco-friendly alternative to traditional plastics and reducing the impact on the environment. Additionally, is resistant to impact and wear, capable of withstanding mechanical stress. It is easily processed through various techniques such as injection molding, extrusion, and 3D printing [8].

Like the previous material, PLA is considered safe for use in contact with food and has been approved by regulatory organizations like the FDA (Food and Drug Administration) for food packaging and food-contact applications. Despite its advantages, is important to note that PLA has moderate mechanical strength and may be more brittle compared to other plastic materials. Therefore, is more suitable for applications with light to moderate mechanical demands. In Table 1 is shown the main material PLA properties ranges [9].

c. PLA with Aluminum is a composite material that combines the biodegradable polymer PLA with aluminum particles and can also be found in the form of filament for 3D printing using FDM technology. This combination results in improved mechanical strength, increased thermal conductivity due to the aluminum, and enhanced rigidity. This material can be used in a wide range of applications, such as various structural components, equipment parts, or objects that require increased strength and efficient heat dissipation [10]. It can also be a solution for robotic equipment that requires soft jaws or, for example, in the case of gripping elements of a pneumatic clamping system. In Table 1 is shown the main PLA with aluminum material properties ranges [9].

d. ABS (Acrylonitrile Butadiene Styrene) is a durable and resistant thermoplastic material, known for its strength against impact and abrasion, is known for its good mechanical properties, including here rigidity and tensile strength [11]. Additionally, is resistant also to chemicals and has good dimensional stability, making it ideal for integration into certain components of industrial robotic grippers. In Table 1 is shown the main ABS material properties ranges [12].

e. TPU (Thermoplastic Polyurethane) is an elastic and flexible thermoplastic material, known for its excellent resistance to abrasion and impact, a tear-resistant polymer that can be deformed without losing its initial properties. Essentially, this material is characterized by its tear strength, durability, and flexibility, making it suitable for applications that require elastic materials [13]. Being a material that has similar mechanical behavior like rubber, TPU is classified into different hardness categories. In this study, two types of materials with different elasticities were used: black TPU 93A and red TPU 82A (the most elastic of the two). In Table 1 is shown the main TPU material properties ranges based on its rigidity [14, 15].

f. UV–sensitive resins such as ANYCUBIC resins are polymeric materials that solidify or harden under the influence of ultraviolet radiation, which are composed of photosensitive monomers that react to exposure to UV light. When the resin is exposed to a UV source, the chemical bonds of the monomers form, thus, resulting in a solid three-dimensional network. A distinctive characteristic of UV-sensitive resins is that they can harden under exposure rapidly and completely with the help of a suitable UV light source, making them ideal for the 3D printing [16]. This photosensitive polymerization process allows to create solid and durable objects in a short period of time without the need for heating or additional treatments. Stereolithography (SLA) technology uses resins as raw material and is the first 3D printing technology invented. UV-sensitive resins can be used in various applications, including the manufacturing of finger grippers or just for the contact surface between a finger gripper and an object. In this study, two types of UV-sensitive resin manufactured by ANYCUBIC were used: one transparent and one with a gray pigment. The aim was to observe whether the integrated pigment in the resin would produce significant differences in the experimental results. In Table 1 is shown the main UV–sensitive resin material properties ranges [17].

Table 1. Main physical properties of the materials used in this study

Properties	**Type of Material**							
	PETG	PLA	PLA + Al	ABS	TPU 93A	TPU 82A	Resin Colorless	Resin Grey
σ (MPa)	20–100	21–60		22.1–74	40	45	23.4	
E (GPa)	1.10–20.3	0.35–3.5		1–2.65	0.62–5.50		0.8–1.2	
ρ (g/cm^3)	1.18–1.37	1–3.41		1.01–1.20	1,21	1,12	1,184 (solid density)	
T_m (°C)	210–260	170–200		180–310	205–235	215–250	~ 150 (normally 3D printed resin does not melt, this value represents the heat deflection temperature of polymers) [18]	

* where: σ is the tensile strength; E is the tensile modulus; ρ is the density; T_m shows the melting temperature (except resins)

2.3. Sample manufacturing process

Different manufacturing technologies were used to obtain the samples. Thus, the manufacturing conditions and characteristics of each 3D printing method will be presented below.

2.3.1. Samples manufactured by using FDM technology

To initiate the additive manufacturing process using the Flashforge Creator Pro printer, was necessary to prepare first a printing file with the printing settings specific to each material used in this study. Therefore, for printing file preparation, the FlashPrint 3D printer software application was used, where the printing properties listed in Table 2 were sequentially configured.

Is worth mentioning that the 3D printer is equipped with an enclosure that helps maintain a constant temperature throughout the printing process. Additionally, as can be observed from the data provided in

Table 2, the same printing settings were maintained regarding perimeter shells, top and solid layers, fill density, and fill pattern (although this aspect becomes irrelevant since full infill was chosen for the samples).

Table 2. Material printing settings used in this study

Printing Properties	**Type of Material**					
	PETG	PLA	PLA + Al	ABS	TPU 93A	TPU 82A
Layer Height (mm)	0.2	0.12	0.12	0.12	0.2	0.2
First Layer Height (mm)	0.2	0.2	0.2	0.2	0.2	0.2
Number of Perimeter Shells	3					
Number of Top Solid Layers	4					
Number of Bottom Solid Layers	4					
Fill Density (%)	100					
Fill Pattern	Line					
Filament diameter (mm)	1.75					
Print Speed (mm/s)	20	50	50	60	20	20
Travel Speed (mm/s)	30	70	70	70	30	30
Extruder Temperature (°C)	230	200	200	230	230	230
Platform Temperature (°C)	50	50	50	80	50	No heating

Table 3. The estimated and effective used material and printing time of the samples

Samples	**Estimated Material Used [m]**	**Effective Material Used, [m]**	**Estimated Printing Time**	**Effective Printing Time**
PETG	8.86	8.8554	3 h 44 min	3 h 38 min
PLA	8.84	8.8443	2 h 46 min	2 h 41 min
PLA + Al	8.84	8.8443	2 h 46 min	2 h 41 min
ABS	8.84	9.6115	2 h 25 min	2 h 26 min
TPU 93A	8.86	8.8562	3 h 45 min	3 h 39 min
TPU 82A	8.86	8.8562	3 h 44 min	3 h 38 min

As for the parameters related to layer height, they were adjusted for PETG and TPU to facilitate the printing of these materials, which are more challenging to print using FDM. In the case of ABS, since is a material that tends to shrink and can present adhesion issues to the printing bed, a bottom support was added to eliminate these potential problems during printing (Figure 2d). In Table 3, the estimated material used in manufacturing the samples and the effective one is compared, along with the printing time estimated by the slicing software and the effective one.

In Figure 2, the printed samples can be observed upon completion of the 3D printing process, corresponding to each previously mentioned material. For the PETG and TPU 93A samples, a BuildTak adhesive sheet was used to eliminate the adhesion issues to the printing bed (Figure 2a and e).

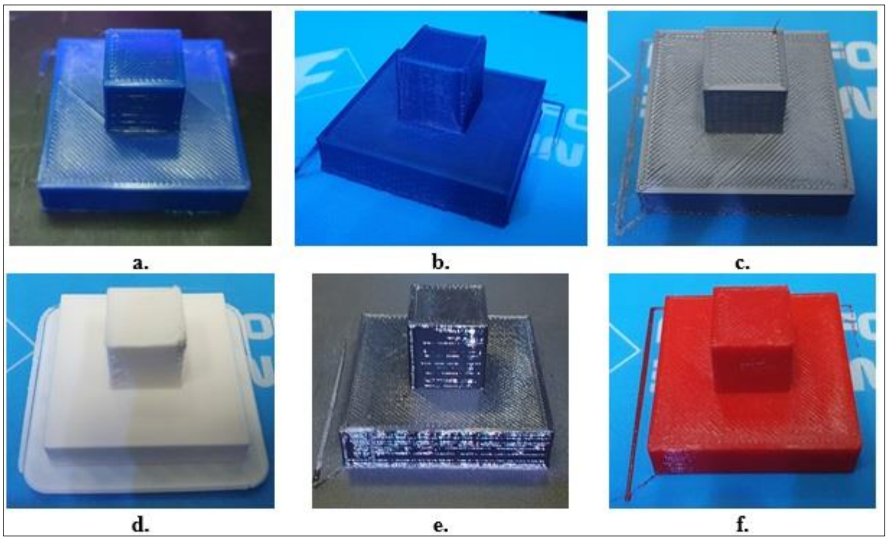
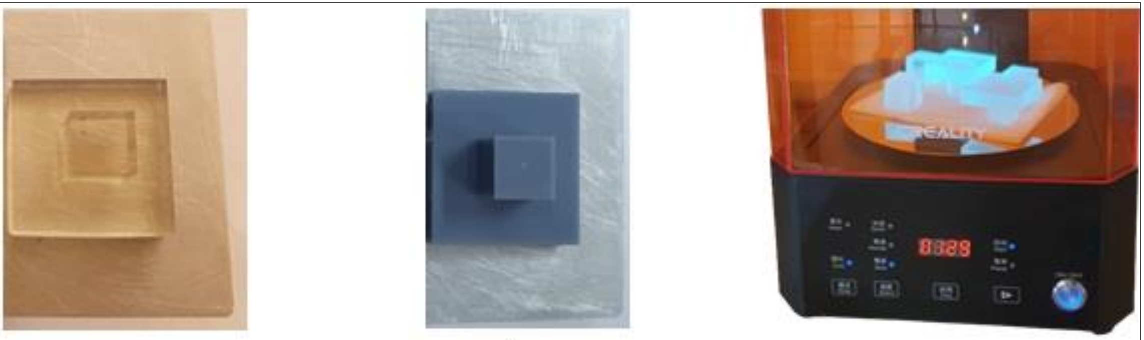


Figure 2. 3D printed samples by using FDM technology. a. PETG sample; b. PLA sample; c. PLA with Aluminum sample; d. ABS sample; e. TPU 93A sample; f. TPU 82A sample

2.3.2. Samples manufactured with SLA technology

In the case of this 3D printing technology, the sample preparation in the software application of Creality 3D printer was necessary, where the segmentation of the samples was performed. Thus, for both types of Anycubic UV–sensitive resins, colorless and grey, the following printing settings were chosen in the Halot Box software application: consumable (normal); layer height (0.05 mm); B-Offset thickness (0.5 mm); B-Offset focal length (198 mm); XY compensation (0.00); Anti-Aliasing Enabled.

The approximate printing time was 2 h and 56 min, and upon completion of the printing, the samples were cleaned with isopropyl alcohol and cured with UV light for 2 min using the Creality post–processing equipment to enhance their strength. It is worth noting that the sample made from clear resin acquired a slight yellowish tint after the UV curing process. Figure 3 shows the samples obtained after the 3D printing with SLA process and the post–processing method used in this case.



a. b. c.

Figure 3. 3D printed samples by using SLA technology. a. Colorless resin sample; b. Grey resin sample; c. Samples curing process

2.3.3. C45 alloy steel disc

This material is a type of high–strength carbon steel, known for its high resistance and durability, which gives it superior mechanical properties [19]. In this way a small disk of 66 mm in diameter and 10 mm height, with a catch leg was used in this study. The C45 steel alloy was chosen because is recognized for its resistance to wear, dimensional stability, and its ability to withstand multiple mechanical stress, making it an optimal material for industrial gripper manufacturing.

2.4. Preparing the equipment to conduct friction experiments

During these tests, the bottom part of the sample was used, specifically the surface built in direct contact with the printing bed, due to its flatness. The plastic material sample was fixed in a clamping system located on the CETR UMT-2 tribometer, ensuring the flatness of both, sample and clamping system. On the top part of the equipment, the disc made of C45 alloy steel was fixed using a clamping pin.

Measurements were performed in two orthogonal directions for each plastic material sample, applying a constant force of 50N and 150N, and conducting two sets of tests with the following input parameters: two velocities were used, 0.1 mm/s and 1 mm/s in both sets of tests; the duration of the experiments was approximately 5-6 s per sample, depending on the analyzed material. Figure 4 illustrates the method of sample fixation on the tribometer.

Figure 4. Preparing the tribometer to conduct friction experiments

3. Results and discussions

In Table 4 below, the results that have been diligently gathered are displayed. The data was systematically collected and analysed to ensure the validity of the findings. Each data point has been scrutinised and interpreted investigated, with the findings compiled and laid out in a manner that should aid comprehension. It is hoped that this table will allow for clear insights and enhanced understanding of the study's outcomes.

Table 4. Coefficient of friction values for the studied materials

Samples	Friction Coefficient Values			
	V= 0.1 (mm/s), F=50(N)	V= 1 (mm/s), F=50(N)	V= 0.1 (mm/s), F=150(N)	V= 1 (mm/s), F=150(N)
PETG 1	0.171	0.138	0.147	0.134
PETG 2	0.167	0.141	0.151	0.127
PLA 1	0.146	0.120	0.123	0.080
PLA 2	0.16	0.111	0.122	0.112
PLA+AL 1	0.152	0.126	0.108	0.073
PLA+AL 2	0.171	0.125	0.124	0.103
ABS 1	0.102	0.072	0.071	0.080
ABS 2	0.117	0.068	0.067	0.056
TPU 93A 1	0.199	0.172	0.193	0.179
TPU 93A 2	0.210	0.176	0.20	0.176
TPU 82A 1	0.297	0.207	0.255	0.216
TPU 82A 2	0.326	0.221	0.277	0.218
GREY RESIN 1	0.121	0.111	0.112	0.105
GREY RESIN 2	0.120	0.117	0.124	0.116
COLOURLESS RESIN 1	0.129	0.125	0.117	0.124
COLOURLESS RESIN 2	0.131	0.117	0.108	0.113

Each material was analysed in two orthogonal directions, indicated by a '1' or '2' following the material name, reflecting the inherent anisotropy of these materials.

For each material and direction, friction coefficients were measured under two different sliding velocities (0.1 mm/s and 1 mm/s) and under two different normal forces (50N and 150N).

The systematic measurement of these values allowed for an assessment of the material properties under different tribological conditions, thereby providing a comprehensive understanding of their behaviour. In the analysis of ABS, both in the '1' and '2' orientations, it was observed that the friction coefficients were relatively low. Under a force of 50N, at a velocity of 0.1 mm/s, friction coefficients of 0.102 and 0.117 were recorded for ABS 1 and 2 samples. With an increase in velocity to 1 mm/s, the friction coefficients decreased to 0.072 for ABS 1 and 0.068 for ABS 2.

MATERIALE PLASTICE
https://revmaterialeplastice.ro
https://doi.org/10.37358/Mat.Plast.1964

When the normal force was raised to 150N, the friction coefficients for ABS 1 and 2 were found to be 0.071 and 0.067 at 0.1 mm/s, and 0.08 and 0.056 at 1 mm/s, respectively. Regarding PETG, at a velocity of 0.1 mm/s under a force of 50N, a noticeable increase in the friction coefficients was recorded compared to ABS, with values of 0.171 for PETG 1 and 0.167 for PETG 2.

This increase was maintained at a velocity of 1 mm/s, with friction coefficients of 0.138 for PETG 1 and 0.141 for PETG 2. Upon raising the normal force to 150N, PETG 1 and 2 showed friction coefficients of 0.147 and 0.151 at 0.1 mm/s, and 0.134 and 0.127 at 1 mm/s, respectively.

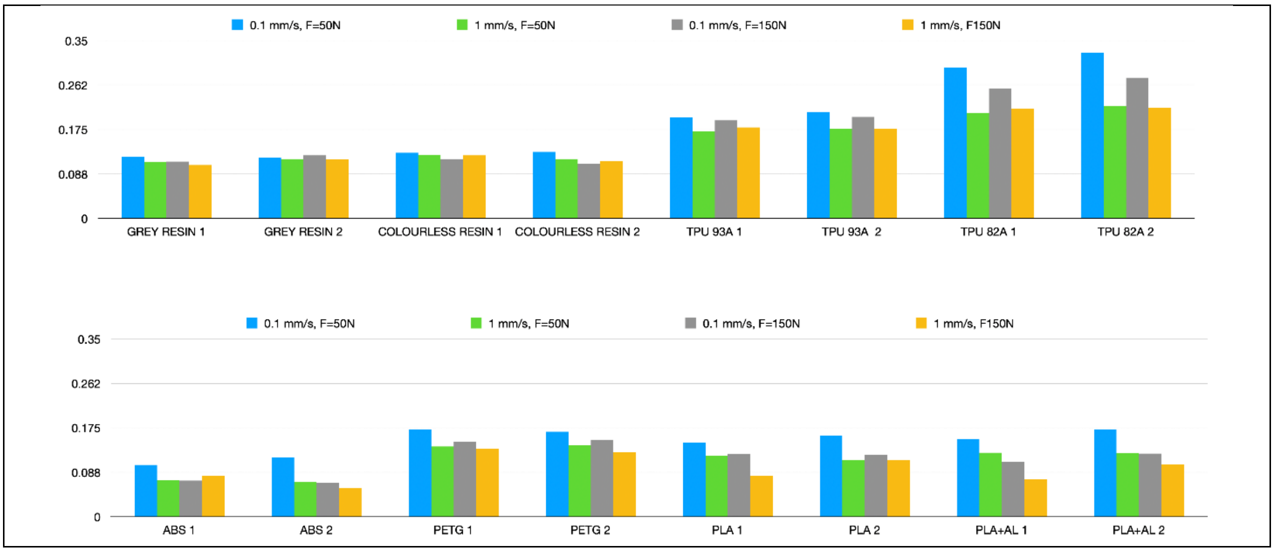


Figure 5. Graphic representation of test results

In terms of PLA, a friction coefficient of 0.146 was determined for PLA 1 and 0.16 for PLA 2 at 0.1 mm/s under a force of 50N. At 1 mm/s, these values fell to 0.12 for PLA 1 and 0.111 for PLA 2. Upon increasing the force to 150N, the friction coefficients at 0.1 mm/s were observed to be 0.123 for PLA 1 and 0.122 for PLA 2, and 0.08 and 0.112 at 1 mm/s.

The PLA + Al composite showed an interesting pattern. At a force of 50N and a velocity of 0.1 mm/s, friction coefficients of 0.152 and 0.171 were registered for PLA + Al 1 and 2. At 1 mm/s, the friction coefficients dropped to 0.126 for PLA + Al 1 and 0.125 for PLA + Al 2. With a force of 150N, friction coefficients of 0.108 and 0.124 were found at 0.1 mm/s, and 0.073 and 0.103 at 1 mm/s for PLA + Al 1 and 2, respectively.

The Grey Resin, at 50N and 0.1 mm/s, exhibited friction coefficients of 0.121 for Grey Resin 1 and 0.12 for Grey Resin 2. These values increased slightly at 1 mm/s, reaching 0.111 for Grey Resin 1 and 0.117 for Grey Resin 2. With a force of 150N, the friction coefficients were 0.112 and 0.124 at 0.1 mm/s, and 0.105 and 0.116 at 1 mm/s, for Grey Resin 1 and 2.

The Colourless Resin presented friction coefficients of 0.129 for Colourless Resin 1 and 0.131 for Colourless Resin 2 at 0.1 mm/s under 50N. At a velocity of 1 mm/s, these values slightly decreased, measuring 0.125 for Colourless Resin 1 and 0.117 for Colourless Resin 2. With a normal force of 150N, the friction coefficients were 0.117 and 0.108 at 0.1 mm/s, and 0.124 and 0.113 at 1 mm/s, for Colourless Resin 1 and 2, respectively.

Regarding TPU 93A, friction coefficients were notably higher. At 50N and 0.1 mm/s, the coefficients were 0.199 for TPU 93A 1 and 0.21 for TPU 93A 2. These values decreased slightly to 0.172 and 0.176 at 1 mm/s. At 150N, TPU 93A 1 and 2 recorded coefficients of 0.193 and 0.2 at 0.1 mm/s, and 0.179 and 0.176 at 1 mm/s. The highest friction coefficients were obtained for TPU 82A as shown in Figure 5. At 50N and 0.1 mm/s, values of 0.297 and 0.326 were recorded for TPU 82A 1 and 2. At 1 mm/s, these decreased to 0.207 and 0.221. When the force was increased to 150N, the coefficients were found to be 0.255 and 0.277 at 0.1 mm/s, and 0.216 and 0.218 at 1 mm/s, for TPU 82A 1 and 2.

4. Conclusions

In summary, a comprehensive investigation of the frictional properties between steel and a range of materials including Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PETG), Polylactic Acid (PLA), Polylactic Acid with Aluminum (PLA + Al), UV-Sensitive Grey Resin, Colorless UV-Sensitive Resin, and Thermoplastic Polyurethane of varying hardness (TPU 93A and 82A) was conducted. It was observed that the friction coefficients varied greatly between materials and orientations, illustrating the effects of different conditions on their performance.

Notably, the material ABS, under the conditions tested, was found to exhibit the lowest friction coefficients, in both its '1' and '2' orientations. A decrease in the friction coefficient was observed as the velocity increased, indicating a negative correlation between sliding velocity and friction for ABS. A further reduction in friction coefficient was also noticed with increased force, suggesting that ABS could potentially perform optimally under high loading conditions. In contrast, PETG and PLA demonstrated moderate friction coefficients. However, it was interesting to note that the PLA + Al composite exhibited a decrease in friction coefficient with increased velocity, similar to ABS, and also under a higher load. This could possibly be attributed to the inherent properties of aluminum, a known low–friction material, combined with PLA. This demonstrates that the choice of material composites can be crucial in achieving specific tribological properties. The resin–based materials, both Grey and Colorless, showed a slight increase in friction coefficient with increased velocity and load. These characteristics might be reflective of their material properties, perhaps due to their hard, brittle nature compared to the more ductile plastics. The TPU materials, on the other hand, presented the highest friction coefficients. Particularly, TPU 82A, exhibited the highest values under all the conditions tested. This could suggest its suitability in applications where high friction is required or advantageous. Nevertheless, the exact implications of these findings would depend greatly on the specific application and operational conditions. It should also be noted that the anisotropy of the materials, represented by the two orientations (1 and 2), played a substantial role in the friction coefficients. This was especially evident for materials such as PLA + Al and TPU 82A, where friction coefficients varied noticeably between the two orientations. Therefore, it is important to consider the material orientation when assessing their tribological performance, especially for anisotropic materials. From this investigation, it has been demonstrated that different materials and conditions will lead to different friction coefficients. It is this diversity that necessitates such investigations, as understanding the effect of velocity, force, material composition, and material orientation on frictional properties is critical in a wide array of applications, from engineering (industrial grippers) to material science. Considering the above, it is concluded that tribological characteristics are an essential consideration in the selection of materials for any application involving surface contact and movement. Furthermore, this study serves to highlight the need for comprehensive tribological testing to predict and understand the behavior of materials under various operating conditions. It is also crucial to extend such analyses to include other factors such as wear rate, environmental conditions, lubrication, and surface finish, as these parameters can also significantly impact tribological behavior.

Conclusively, these findings provide valuable insights into the frictional behavior of these diverse materials against steel. However, it is recommended that further research be conducted to delve deeper into the tribological performance of these and other materials. This could include investigation of other tribological parameters, application of varying load and velocity conditions, and the inclusion of more diverse materials. Furthermore, the effects of long-term exposure to such conditions, which was not covered in this study, could be an interesting avenue for future research. It is through such exhaustive studies that more informed decisions can be made in the selection and design of materials for specific applications, ultimately leading to optimized performance and extended lifespan of components.

References

1. TAI, K., EL-SAYED, A.R., SHAHRIARI, M., BIGLARBEGIAN, M., MAHMUD, S., State of the Art Robotic Grippers and Applications, *Robotics*, 5(2), 2016, https://doi.org/10.3390/robotics5020011.

2. BANES, C., MELLADO, M., BELTRAN, P., Novel Additive Manufacturing Pneumatic Actuators and Mechanisms for Food Handling Grippers, *Actuators*, 3(3), 2016, 205–225;
3. SHINTAKE, J., CACUCCIOLO, V., FLOREANO, D., SHEA, H., Soft Robotic Grippers, *Advanced Materials*, 30(29), July 2018, 1707035, https://doi.org/10.1002/adma.201707035.
4. GUO, J., SUN, Y., LIANG, X., LOW, J.H., WONG, Y.R., TAY, V.S.C., YEOW, C.H., Design and fabrication of a pneumatic soft robotic gripper for delicate surgical manipulation, *2017 IEEE International Conference on Mechatronics and Automation (ICMA)*, Takamatsu, Japan, 2017, pp. 1069–1074, doi: 10.1109/ICMA.2017.8015965.
5.FRANCISZCZAK, P., PIESOWICZ, E., KALNIŅŠ, K., Manufacturing and properties of r-PETG/PET fibre composite - Novel approach for recycling of PETG plastic scrap into engineering compound for injection moulding, 154, December 2018, 430–438.
6. SHILOV, S.Y., ROZHKOVA, Y.A., MARKOVA, L.N., TASHKINOV, M.A., VINDOKUROV, I.V., SILBERSCHMIDT, V.V., Biocompatibility of 3D-Printed PLA, PEEK and PETG: Adhesion of Bone Marrow and Peritoneal Lavage Cells., *Polymers* 2022, 14, 3958. https://doi.org/10.3390/polym14193958.
7.***Overview of materials for PETG Copolyester, https://www.matweb.com, accessed on June 10. 2023.
8. DAVACHI, S.M., KAFFASHI, B., Polylactic Acid in Medicine, *Polymer-Plastics Technology and Engineering*, 54(9), 2015, 10.1080/03602559.2014.979507.
9.***Overview of materials for Polylactic Acid (PLA) Biopolymer, https://www.matweb.com, accessed on June 12, 2023.
10. ZELALEM, L., JOOHEON, K., hermally conductive and highly rigid polylactic acid (PLA) hybrid composite filled with surface treated alumina/nano-sized aluminum nitride, Composites Part A: *Applied Science and Manufacturing*, 124, September 2019, 105506.
11. UMESH, K.V., NAND, J.K., GUPTA, E., GYANENDRA K.S., NAVEEN, A.D., BHUPENDRA, P.S., Optimization of FDM 3D Printing Process Parameters on ABS based Bone Hammer using RSM Technique, *IOP Conf. Ser.: Mater. Sci. Eng.*, 1206, 2021, 10.1088/1757-899X/1206/1/012001.
12.***Overview of materials for Acrylonitrile Butadiene Styrene (ABS), Extruded, https://www.matweb. com, accessed on June 12, 2023.
13.XU, T., SHEN, W., LIN, X., XIE, Y.M., Mechanical Properties of Additively Manufactured Thermoplastic Polyurethane (TPU) Material Affected by Various Processing Parameters, *Polymers* 2020. 12, 3010. 10.3390/polym12123010.
14.*** Filament SmartFil Flex – TPU 93A – Black, Technical Data Sheet.
15.*** Filament FilaFlex Original 82A Red, Technical Data Sheet.
16.STORCK, J.L., EHRMANN, G., UTHOFF, J., DIESTELHORST, E., BLACHOWICZ, T., EHRMANN, A., Investigating inexpensive polymeric 3D printed materials under extreme thermal conditions, *Materials Futures*, 1(1), 10.1088/2752-5724/ac4beb.
17. ***Anycubic UV-Sensitive Resin, Technical Data Sheet.
18.DWAMENA M., Can Resin Prints Melt? Are They Heat Resistant? https://3dprinterly.com/can-resin-prints-melt-are-they-heat-resistant/, accessed: June 26, 2023.
19.VOREL, I., VANČURA, F., PILEČEK, V., JIRKOVÁ, H., MAŠEK, B., Material-technological Modelling of C45 Steel Die Forgings, *Procedia Engineering*, 100. 2015, 714–721, https://doi.org/10.1016/j.proeng.2015.01.424.
20.VOICU, A. D., HADĂR, A., VLĂSCEANU, D., Benefits of 3D printing technologies for aerospace lattice structures, *Scientific Bulletin of Naval Academy*, XXIV, 2021, 8-16, https://doi.org/10.21279/1454-864X-21-I1-001.
21.VASILESCU, M.D., FLESER, T., Influence of Tech. Parametrs on the Dim. of Threaded Parts Gener. with PLA Math. by FDM 3D Printing, *Mater. Plast.*, **55**(4) 2018, 718-722.

Manuscript received: 5.07.2023