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Design and Implementation of Soft Robotic Gripper Using 3D Printing Technology

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Abstract: Automated warehouses rely on robotic systems for efficient order picking, yet object manipulation remains challenging due to variations in object shape, size, and material properties. This study focuses on the material selection for the holder of flexible robotic grippers using fused deposition modelling. The holder plays a crucial role in ensuring a secure fit of the gripper's fingers, which is essential for stable and precise object handling in bin picking applications. Testing specimens were fabricated following the ASTM D638-22 standard with a grid infill pattern at full density. Two different variants of Polyethylene Terephthalate Glycol and Acrylonitrile Styrene Acrylate were tested. Mechanical properties, including ultimate tensile strength, elongation at break, and Young's modulus, were estimated using a universal testing machine. Results indicate that one variant of Polyethylene Terephthalate Glycol exhibited the highest tensile strength (40.54 MPa), making it suitable for applications requiring high mechanical strength and resistance to tensile loads, while Acrylonitrile Styrene Acrylate provided a balance between strength and flexibility. These results illustrate the comparison of materials and how material selection and infill density impact the mechanical performance of the holder, which contributes to a better choice of material. Future research will explore the influence of 3D printing temperatures, layer height and testing other infill patterns to further enhance the efficiency and reliability of materials used for robotic grippers in robotic manipulation.

Keywords: intralogistics; robotization; robotic order picking; robotic gripper; tensile strength testing; 3D printing

1 INTRODUCTION

The global warehouse automation market has grown significantly, surpassing $23 billion in 2023 and is projected to reach $41 billion by 2027, driven by the expansion of E-commerce and increasing consumer expectations [1]. As warehouse operations become more complex, logistics providers are integrating automation and robotics to enhance efficiency, flexibility, and productivity [2, 3]. Among these advancements, robotic order picking, particularly bin picking, has gained attention due to its labour intensive nature and the challenges posed by diverse product shapes, sizes, and materials [4, 5].

In E-commerce and Food Logistics, robotic systems must handle a variety of different objects, from fragile products to heavy electronics that require advanced gripping solutions [6, 7]. Picking robots rely on a proper vision system for object recognition and selected robotic grippers for manipulation of objects [8]. Robotic grippers are categorized into rigid and flexible types; while rigid robotic grippers perform well with uniform objects, they struggle with irregular or delicate objects [9]. Soft robotic grippers, which offer adaptability and precision, are increasingly explored for handling fragile and irregularly shaped objects [10].

Advancements in additive manufacturing, particularly Fused Deposition Modelling (FDM), have enabled the rapid development of robotic components, including robotic grippers [11, 12]. A robotic gripper typically consists of a holder, fingers, and actuators for pneumatic or electrical operation [13]. The holder, which connects the robotic gripper to the robotic manipulator, plays a critical structural role. Selecting an optimal material for the holder is essential to ensure mechanical strength, durability, and cost-effectiveness [12].

Polyethylene Terephthalate Glycol (PETG) and Acrylonitrile Styrene Acrylate (ASA) are widely used in 3D printing due to their distinct mechanical properties. PETG offers impact resistance and transparency, while ASA provides high strength and UV resistance, making it suitable for demanding applications [14, 15]. When printed with 100% infill density, these materials exhibit mechanical properties that are crucial for optimizing robotic gripper holders [16].

This study compares the mechanical performance of PETG and ASA for a robotic gripper holder, focusing on tensile strength, elongation at break, and Young's modulus. Specimens were 3D printed following ASTM D638-22 standards [17] and tested to determine their performance. The proposed research aims to answer: How do material type, infill density, and infill pattern affect the mechanical properties of materials, and how can these insights help in selecting the proper materials for developing a holder for a robotic gripper? In summary, this research aims to assess and benchmark different materials for the holder of the robotic gripper by systematically analysing the mechanical properties of 3D-printed samples.

2 LITERATURE REVIEW

The integration of robotic systems in industries such as E-commerce, Healthcare, and Manufacturing has accelerated, particularly in order picking, where robotic grippers play a crucial role [5, 12, 13, 18]. Among them, soft robotic grippers have gained attention due to their adaptability and ability to handle fragile and irregularly shaped objects [18, 19]. Compared to rigid robotic grippers, they offer better compliance and require fewer control complexities, making them more effective in handling diverse warehouse items [19]. However, optimizing the soft robotic gripper design remains a challenge, requiring precise material selection and numerical simulations to check durability and better performance [20].

3D printing, particularly Fused Deposition Modelling (FDM), has been widely adopted for fabricating flexible robotic grippers due to its flexibility in material selection and rapid prototyping capabilities [21]. Recent studies emphasize the role of 3D printing parameters, such as infill density and pattern, in determining mechanical performance [22-24]. Research has shown that infill patterns significantly affect structural integrity, with optimized designs increasing strength up to four times compared to less efficient geometries [23]. However, existing studies largely focus on designing robotic grippers, with limited research on comparing such as material type, infill density, and infill pattern for various materials.

Studies on 3D-printed materials have assessed mechanical properties using standardized methods such as ASTM D638-22 for tensile testing, which evaluates tensile strength, elongation at break, and Young's modulus [17]. Pyka [25] examined eight FDM filaments for biomedical applications, highlighting variations in mechanical behavior, while Georgopoulou [10] explored TPU-based flexible structures with integrated sensors. These findings suggest the need for further research into material-specific behaviours, particularly for industrial robotic applications.

Despite these advancements, research on robotic gripper holders remains limited, particularly in assessing how different 3D printing materials such as PETG and ASA affect mechanical properties under various infill conditions. By analyzing stress, tensile strength, and deformation under standardized testing, our research examines the mechanical properties of different materials to aid in the selection of suitable materials for robotic gripper holders, ensuring enhanced strength and durability for robotic manipulation.

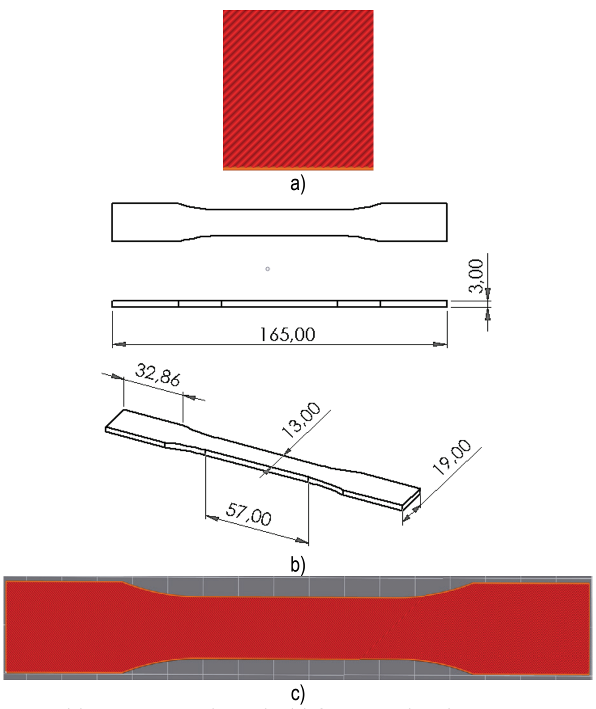

Figure 1 (a) Detailed view of the infill, (b) Geometry of the 3D printed specimen (measurements in mm), and (c) Slicing profile of the 3D printed specimen.

3 METHODOLOGIES

3.1 Specimen Preparation

To ensure mechanical comparability, all specimens were printed at 100% infill density using a grid pattern. ASA (Prime Natural) and PETG (Transparent and Original Lipstick Red) were selected as experimental materials. Based on manufacturer guidelines, a 0.4 mm nozzle and a printing temperature of 250 °C were applied uniformly for all samples. All samples were printed according to the ASTM D638-22 standard [17] in the form of dog bone-shaped specimens. A grid was used as the filling pattern. Fig. 1 illustrates the specimen geometries, dimensions (in mm), and slicing profiles.

The slicer used for printing the specimens was Creality Print V5.1 to generate the G-code, with settings based on the printer manufacturer's recommendations [26] and prior research to ensure consistent mechanical properties and reliable printing quality [27]. Tab. 1 lists the main 3D printing parameters used to produce samples with a grid fill pattern. The layer height was maintained at 0.24 mm, while the first layer was printed at a slightly lower height of 0.2 mm to enhance bed adhesion. The printing speed was set at 70 mm/min to balance precision and efficiency, while the printing bed temperature was maintained at 60 °C to ensure proper adhesion and minimize warping.

Table 1 Printing parameters used for fabrication testing samples

Parameter	Value
Nozzle diameter	0.4 mm
Print temperature °C	250
Layer height	0.24 mm
First layer height	0.2 mm
Infill density	100%
Infill pattern	Grid
Printing speed	70 mm/min
Printing bed temperature	60 °C

3.2 Equipment's Used

The specimens were printed using the Creality K1 Max [28] with parameters. As shown in Tab. 1, the parameters were set according to the manufacturer's recommendations and matched with the printer settings. The printer is equipped with a 0.4 mm nozzle and has maximum nozzle temperatures of 230 °C for TPU and 250 °C for the other materials. In total, three specimens were printed following ASTM D638-22 standards. Tensile testing was conducted using the Zwick Roell Vibrophore 100, where key mechanical properties including ultimate tensile strength, elongation at break, and Young's modulus were evaluated. These properties were chosen because ultimate tensile strength indicates the maximum load the material can bear, elongation at break reflects its ductility and deformation behaviour, and young's modulus provides a measure of its stiffness. Collectively, these metrics offer critical insights into the robotic gripper holder's performance, ensuring that it can withstand operational stresses without failure or excessive deformation [29].

3.3 Experimental Setup

For the preparation of the specimens, 2 materials were used: PETG and ASA. The 3D printing parameters, including infill density, printing temperature, and infill pattern, were carefully selected to ensure optimal mechanical performance. This approach allows for the evaluation of the most suitable material for the soft robotic gripper's holder. For preliminary testing, a single specimen per material was printed and tested. This allowed for an initial assessment of mechanical properties before conducting a larger-scale statistical analysis. Future studies will include at least three specimens per material to improve accuracy and minimize variability. The CAD model for the specimen was designed using SolidWorks 2024 software, following ASTM D638-22 Type I tensile test standards. The specimen used and the image for the printed samples are shown in Fig. 2.

Figure 2 Printed specimens for the tensile test

For the preparation of the experiment and to ensure accurate results presented in Tab. 3, the measurement data for the width and thickness of each specimen were calculated for each material.

Table 2 Measurement data for the specimens

Sample name	Material type	Width (mm)	Thickness (mm)
030111	PETG Original Lipstick Red	13.2	3.00
030211	PETG Transparent	12.99	3.01
040011	ASA Prime Natural	12.57	2.97

Tab. 2 shows the sample names, materials used, and dimensions of each specimen, with width and thickness measurements calculated individually to account for variations and ensure accuracy.

4 RESULTS AND ANALYSIS

The geometry of the tensile specimens was designed in SolidWorks 2024 in accordance with the standard test method for tensile strength of plastics (ASTM D638-22) [17]. Specimens were tested using a Zwick Roell Vibrophore 100 universal testing machine [29]. The Vibrophore 100 is a high-frequency testing machine that can perform both dynamic and static material tests and has a load capacity of 100 kN [30]. The testing system was configured with testXpert III software, which automatically recorded the test data and generated graphical results. The most important parameters measured during the tests were the ultimate tensile strength (MPa), the yield strength (MPa) and the test duration (seconds).

During the tensile tests, a strain extensometer was used to accurately measure the deformation (strain) of the individual specimens [31]. An extensometer was attached to the specimen mounted on the Vibrophore 100. It tracked the change in length as the applied load increased. This precise measurement of strain is essential for the calculation of mechanical properties such as modulus of elasticity, yield strength and elongation at break. The extensometer ensured that the recorded data reflected the true behaviour of the material and reduced errors that could occur if displacement were measured only at the grips [32]. The testXpert III software was configured with the initial test parameters to achieve accurate results. The tests were conducted under controlled laboratory conditions at a room temperature of approximately 20 °C, with small variations of ±1–2 °C. The graph on Fig. 4 presents the experimental results, comparing standard stress (MPa) and strain (%).

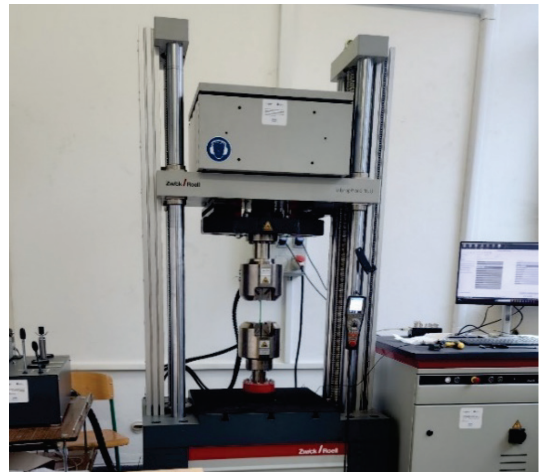

Figure 3 Tensile tests performed in the laboratory to evaluate the mechanical properties of the tested materials. The setup includes a universal testing machine applying controlled tensile forces while measuring elongation and stress response

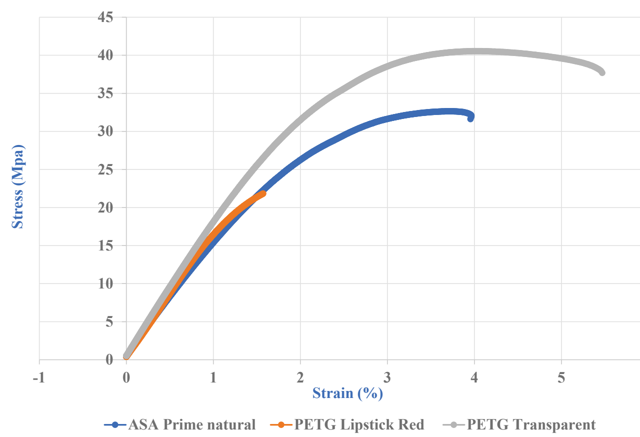

Figure 4 A graphical representation of the tensile test results for the materials tested (ASA Prime Natural, PETG Original Lipstick Red, and PETG Transparent)

The stress-strain curves on Fig. 4 illustrate the mechanical differences between the tested materials. The *x*-axis represents strain (%), which is the elongation normalized by the original length, while the *y*-axis represents stress (MPa), which is the applied force divided by the measured cross-sectional area. PETG original lipstick Red (orange curve on Fig. 4) shows lower tensile strength and a lower strain at fracture, indicating brittle behaviour. PETG Transparent (grey curve on Fig. 4) exhibits higher stress and strain or elongation, making it more ductile and mechanically superior. ASA Prime Natural (blue curve on Figure 4) exhibits lower strain than PETG Transparent but higher than PETG Original Lipstick Red, with strength values between the two, indicating a moderate balance between strength and flexibility.

The tabular results, automatically generated by the testXpert III software, provide the $Rp_{0.2}$, and Rm (yield strength and ultimate tensile strength in MPa), as shown in Tab. 3.

Table 3 Table 3 presents the experimental test results

Material	Yield Strength (MPa)	Ultimate Strength (MPa)
ASA Prime natural	21.03	21.83
PETG Transparent	29.76	40.54
PETF original lipstick red	20.76	27.84

Tab. 3 shows that PETG Transparent had the highest yield strength (29.76 MPa) and ultimate tensile strength (40.54 MPa), indicating its superior mechanical strength compared to the other materials tested. ASA Prime Natural exhibited moderate values ($Rp_{0.2}$ = 21.03 MPa, Rm = 21.83 MPa), while PETG Original Lipstick Red had the lowest values ($Rp_{0.2}$ = 20.76 MPa, Rm = 27.84 MPa), suggesting lower resistance to tensile forces.

However, factors like instrument accuracy, operator variability, and environmental conditions (e.g., temperature and humidity) could introduce measurement uncertainties. Future experiments could improve reliability through multiple trials, machine calibration, and controlled environments. The manufacturer-provided data for the tested 3D printing materials includes values for yield strength, tensile strength, and tensile modulus. For ASA Prime Natural, the yield strength is 30.1 MPa, tensile strength is 37.6 MPa, and tensile modulus is 2100 MPa. Both PETG Transparent and PETG Original Lipstick Red have identical values for yield strength (37.5 MPa), tensile strength (56.7 MPa), and tensile modulus (2100 MPa) for the former and 1900 MPa for the latter [26]. The test results obtained did not include tensile modulus E, but tensile modulus was determined by calculating the tangent of the linear portion of the stress-strain curve and compared with the manufacturer's specifications. A comparison between the tensile modulus values obtained from our tests and the manufacturer-provided data for the 3D-printed specimens reveals significant relative deviations. The relative deviation was calculated based on the standard statistical definition for standard deviation [35]. PETG Transparent (030211) exhibited a tensile modulus of 1800 MPa, with only a 5.26% relative deviation from the manufacturer's value of 1900 MPa.

Table 4 Manufacture data with tensile, yield strength and tensile modulus (E)

Material	Calculated tensile modulus (MPa)	Tensile modulus from manufacturer data (MPa)	Relative deviation (%)
PETG (Original Lipstick Red)	1750	2100	–16.67%
ASA (Prime Natural)	1500	2100	–28.57%
PETG (Transparent)	1800	1900	–5.26%

PETG Original Lipstick Red (030111) showed a tensile modulus of 1750 MPa, 16.67% lower than the expected 2100 MPa. The most significant discrepancy was seen in ASA Prime Natural (040011), where the tensile modulus was 1500 MPa, a 28.57% relative deviation from the expected value.

These differences may be due to factors such as incorrect 3D printing parameters, layer height, environmental conditions during testing or inherent material inconsistencies [23]. The smaller relative deviation in PETG suggests it keeps its strength well during testing. In contrast, the higher relative deviation in ASA might show that it's more affected by 3D printing settings like print speed, temperature, and layer height. Future investigations into the influence of printer settings and infill patterns could provide further insight into these relative deviations. Overall, the experimental results indicate that the 3D-printed ASA and PETG samples exhibited lower mechanical properties than the manufacturer's values, with PETG Original Lipstick Red showing the most significant reductions. PETG Transparent performed better, with a tensile modulus closest to the expected value, while ASA Prime Natural had the largest relative deviation.

During the initial phase of testing materials for the holder of the robotic gripper, the results showed variability compared to the manufacturer's provided data. The discrepancies can be attributed to several factors, including the incorrect printer settings and printing temperature, infill pattern, specimen design, and material properties. For instance, selecting an appropriate infill pattern, such as a line pattern, could have improved the consistency of mechanical properties. Additionally, testing multiple samples with different infill patterns (lines) and in different infill orientations such as latitudinal, transverse, and inclined orientations would have provided a more comprehensive understanding of the material's behaviour. To enhance the accuracy and reliability of the results, future research should involve testing a broader range of samples and materials under varied conditions.

5 CONCLUSIONS

This study investigated the mechanical properties of 3D printed materials (PETG and ASA) for the holder of the robotic gripper. The results showed that PETG Transparent had the highest tensile strength (40.54 MPa) and yield strength (29.76 MPa), making it the most robust material for applications requiring high mechanical performance. ASA Prime Natural showed moderate strength, while PETG Original Lipstick Red showed lower tensile strength, indicating that it is more suitable for less demanding tasks.

The relative deviations between experimental results and manufacturer data, particularly in tensile modulus, highlight the influence of 3D printing parameters, such as layer adhesion and infill patterns, on material performance. These findings emphasize the need for optimized printing conditions to achieve mechanical properties closer to theoretical values.

According to findings from [23], printing temperature and infill orientation significantly affect tensile strength and modulus. Although our study employed only a single combination of printing parameters, the observed deviations from the manufacturer-provided mechanical properties suggest that factors such as layer height, printing temperature, and infill patterns could be responsible. While a systematic parametric study was not performed, the discrepancy indicates that suboptimal or non-standard settings may have influenced the results, consistent with findings in the literature. Research suggests that using a line infill pattern with longitudinal, transverse, and inclined orientations improves material strength and consistency. This comparison confirms that printing parameters play a key role in mechanical performance.

5.1 Future Work

Future research should examine how different printing parameters, such as temperature, velocity, print orientation, and nozzle orientation, affect print quality. It is also recommended to print with a single or double outer layer (commonly referred to as the 'shell') to achieve accurate and consistent mechanical results, as the number of outer walls can significantly influence the structural integrity, tensile strength, and durability of the printed part. This approach was also adopted by [23] in their study on the influence of infill parameters on mechanical properties. Material selection is also important, considering factors like strength, flexibility, durability, and resistance to environmental conditions. The selected material, whether PETG or ASA, should meet the specific needs of the robotic gripper.

Based on previous research, ensuring accurate and reliable testing requires adherence to ISO standards, such as ISO 527 [33] and ISO 178 [34] . Testing should include proper material drying before the experiment, controlled cooling after the experiment, and conducting at least three to five repetitions to account for variations and ensure accurate results.

For improved mechanical performance, future studies may consider exploring full range of recommended printing bed and nozzle temperatures, as higher temperatures can enhance interlayer bonding and reduce voids when properly controlled. However, this should be validated experimentally, as the optimal settings may vary depending on the material and printer. Printing speed of up to 300 mm/s, and assess the impact of different printers, slicers, and cooling levels (fan settings based on material manufacturer recommendations) should be considered. These findings will help develop strong and reliable holders of robotic grippers while showing the potential of 3D printing for cost-effective and customized components for robotic manipulation.

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