3D-PRINTED ADAPTER FOR A ROBOT GRIPPER: DECISIONS AND FAILURES

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The paper presents the development process of a 3D-printed adapter for the pneumatic magnetic gripper of an industrial robot and discusses how the design and manufacturing decisions were made based on the 3D printing process particularities and on the analysis of adapters' failures. The trade-offs between adapter designs, its mechanical strength, the form and dimensional accuracy and printing time are detailed and discussed. Disseminating the good practice in this field is beneficial for reducing the iterations associated to the development process of similar 3D-printed functional parts. The experienced acquired during the development and implementation of this adapter was used in other applications.

Keywords: 3D printing; robotics; design; gripper adapter; process parameters; failures

1. Introduction

On-demand and distributed manufacturing as business models focused on getting what you need when you need it and where you need it, has gained the interest of engineers and companies, being currently enabled by Additive Manufacturing (AM) technology [1, 2]. Reduced supply chain, less inventory and customized responsiveness to specific requirements are provided by AM and offer important competitive advantages [3-4].

Metal-based AM processes such as Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS) or Electron Beam Melting (EBM) are nowadays producing high-quality end-use parts complying with the functional requirements of different applications [5-7], in low volumes or as prototypes. The disadvantage is the high cost of the equipment and materials associated to these processes. In this sense, lower costs are reported when the AM based on the material extrusion (process colloquially known also as 3D printing – 3DP) is used for manufacturing end-use parts, high-performance plastics like Polyetherimide (PEI), Polyetheretherketone (PEEK), Polyphenylenesulfide (PPS) or Polyphenylsulfone (PPSU) being some of the materials suitable for functional applications [8].

Establishing the optimal design in corroboration to the process parameters settings for ensuring the required properties and functionality of the 3D-printed

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end-use products is a complex task. The outcomes are dependent on a multitude of interconnected factors: material, build orientation, process parameters, post-processing operations, each of these influencing prints' performances (mechanical properties, dimensional and form accuracy, surfaces quality, etc.) [9-10]. Furthermore, the data on 3D prints behavior dependence on process parameters is studied based on specimens and rarely on functional parts; hence the difficulty and the prudence in using 3D-printed parts for robotic applications.

Currently, designing and manufacturing of 3D-printed end-use parts are mainly based on engineers' know-how and on a trial and error process. Analyzing and understanding the failures of 3D prints becomes mandatory for gathering the knowledge that would reduce the design iterations, printing time and material consumption. This is the objective of the current paper reporting the development and use of a 3D-printed adapter for the dual pneumatic magnetic gripper of an industrial robot. Documenting the decisions made during the implementation of different adapter models serves as guide for similar applications.

Linking 3DP and robotics is a relatively novel line of work. The following main applications were identified from the reviewed literature: robots as 3D printers [11-12]; robots for loading/unloading 3D printers [13-14]; 3D-printed robots for education [15]; 3D-printed soft grippers or personalized grippers – fully compatible with the idea of personalization specific to AM technology, currently providing the largest number of applications [16-18]; 3D-printed prototypes of robots [19] or for industrial robots (end-effectors/grippers adapters) [20].

The development of 3D-printed adapters for robots' grippers is a topic not frequently addressed in literature, although such parts can be used as solution in different implementation stages of the robot in the production cell or in specific circumstances (as a temporary solution in case of supplies chain interruptions or delays – distributed manufacturing). The adapters are designed based on the engineers' experience and on the results of many tests performed in working conditions, but this knowledge is not usually detailed and made available outside the implementation team. The current article is aimed to fill this gap.

The following challenges were related to this task:

1. Establish the adapter design that fulfills the application functional requirements
2. Find the set of 3DP process parameters that:
   2.1. Ensure the part resistance to the forces and accelerations generated by robot movements
   2.2. Ensure a short manufacturing time and a competitive cost for the adapter.

2. Robotic application description

A Kawasaki RS080N robot is integrated in a cell for loading/unloading steel bars in an automatic lathe (Fig. 1). Two pneumatic magnets (Ixtur, Fi) are used for manipulating round steel bars with diameters of 25-63mm and maximum 40 kg payload. One of the pneumatic magnets grips a steel bar from the conveyor (Fig. 1a) and loads it in the lathe after the other pneumatic magnet removes the machined bar from the chuck (Fig.1b). The machined bar is then placed into a wood box and the whole cycle is resumed.

a .

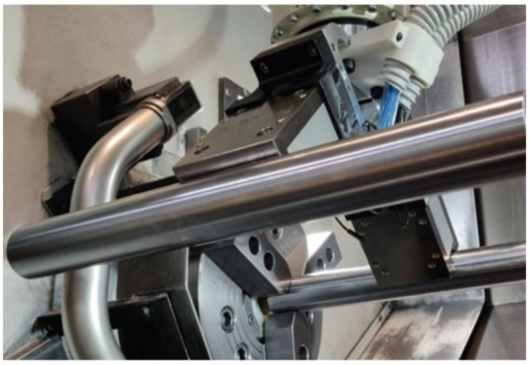

b.

Fig. 1. Application: a. robotic cell, b. dual gripper loading/unloading the lathe

Computer-aided engineering tools are nowadays commonly used for design analysis and optimization purposes before actually manufacturing and testing the product. However, a finite element analysis (FEA) approach could not be properly applied to this 3D-printed adapter first of all because of the current limits in accurately modeling the interior geometry of the layers based on gyroid or grid patterns at different infill densities and number of contours, as used in this research for reducing adapter mass, printing time and stiffness. The adapter is not manufactured fully solid. Even assuming a perfect bond between the filament strands, there is also the aspect of the anisotropy, specific to the 3DP material extrusion process, which needs to be taken into consideration for a correct FEA [21]. Moreover, determining the engineering data for 3D-printed ABS by performing mechanical tests on specimens in different build orientation [22] and then extending these results on large parts with complex geometries should be made with caution. Considering that a finite element model for the adapter is made available, still the validation of this model should be performed for different 3DP parameter settings which require building and testing many parts, similarly to the trial-and-error approach proposed for this case study.

3. Robotic end-effector adapter design

3.1. Adapter design constraints

Based on the functional requirements of the robotic cell, two identical adapters were needed for connecting the aluminum flange with the pneumatic magnets (Fig. 2). Thus, the first design specification considered the interfaces between the adapter and the aluminum flange, respectively between the adapter and the pneumatic magnet (contact surfaces, holes diameters and positions). The pneumatic magnet is assembled with the adapter using four M4 × 20 mm bolts, while the adapter is connected to the aluminum frame with four M6 × 20 mm bolts and two centering bushes (Bosch Rexroth, Ge) with an outer diameter of 10 mm. Centering surfaces were later added to the adapter design for correctly mounting the magnets and for eliminating their relative movements which had a negative impact on positioning accuracy and repeatability. Another design constraint was the adapter through pocket of minimum 20 mm height, accommodating the hoses supplying air to the magnet. The adapter height was dependent on the box dimensions and its slope. The required tolerance of the steel bars fit in the lathe fixture was 0.4 mm.

In Fig. 3 are presented several 3D-printed adapters in different applications. This case study is discussing the first implementation and the development process of the corresponding adapter (Figs. 1-2). The experience acquired allowed a significant shortening of the design and manufacturing process of the adapters for the other applications for which only simple modifications of the design parameters were needed, similar 3DP process settings being used.

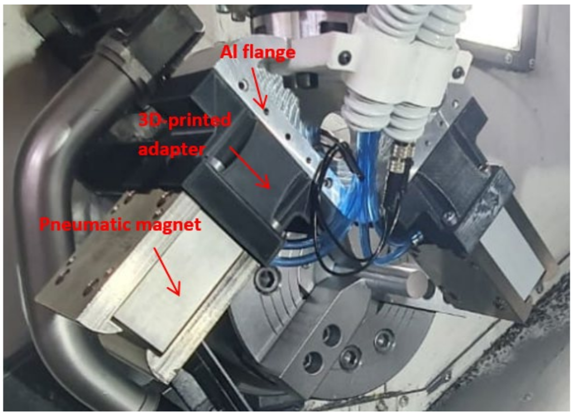


Fig. 2. End-effector assembly: pneumatic magnets, adapters and aluminum flange

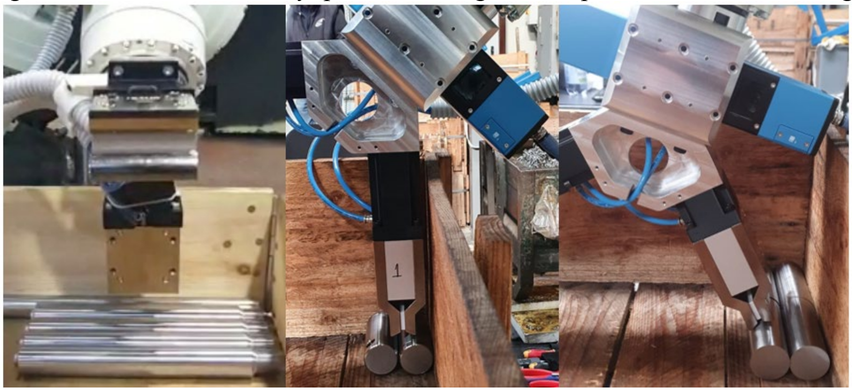


Fig. 3. 3D-printed adapters in different applications

3.2. Adapter design variants

Autodesk Fusion 360 software was used for the 3D modeling process of the adapter. Several versions were designed and manufactured to accommodate the functional requirements described above. The differences in the adapter design variants referred to the geometry of the contact zones with the pneumatic magnets and the shape of the reinforcements between the two features that ensure the connection with the aluminum flange, respectively with the pneumatic magnets (Fig. 2). The adapters' failures occurred during functioning determined both design changes and modifications of 3DP parameters settings.

The first design of the adapter (version 1, Fig. 4a) included only horizontal and vertical faces and no centering features on the surfaces in contact with the pneumatic magnet. In the second version, centering was provided on the contact surfaces with the pneumatic magnet (version 2, Fig. 4b) and two reinforcements were added. The design and process parameters modifications were based on the analysis of the breaking zones, in this sense more details being provided in the next section.

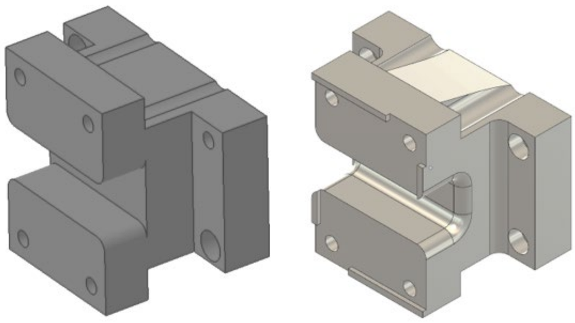


Fig. 4. Virtual 3D models of adapter: a. version 1, b. version 2

4. 3D printing the adapter

The adapters were 3D-printed on a dual extruder Raise3D Pro2Plus printer (Raise 3D Technologies, Inc. USA) with a working space of 305 mm × 305 mm × 605 mm. The material was ABS (Raise 3D Technologies, Inc., USA), filament of 1.75 mm diameter. Table 1 lists the process parameters varied during tests, as well as the main parameters used for manufacturing adapters. For all the other process parameters, the defaults values from the IdeaMaker proprietary slicer were kept. The values of extrusion temperature, platform temperature and deposition speed were established based on the previous experience with the same material, and provided a good adhesion of the adapter to the printer bed and a good bonding between the deposited threads. The value of layer thickness was selected as a compromise between the dimensional and form accuracy of the 3D-printed adapter [23] and the printing time. With these parameters fixed, the next decisions focused on the build orientation and the values of other parameters that impact the printing time and mechanical behavior, i.e. infill density, infill pattern and number of contours [24-25].

Table 1

3D printing process parameters for the adapters

Constant process parameters	Variable process parameters
Layer thickness: 0.2 mm Extrusion temperature: 245°C Platform temperature: 115°C Deposition speed: 60 mm/s Platform adhesion: raft	Number of shells: 3; 6 Infill density: 40%; 50%; 60% Infill type: grid; gyroid

The positioning accuracy and diameter tolerance of the adapter's fixation holes were also important aspects to consider as these holes serve for assembling the adapter to the aluminum flange and pneumatic magnet. Meeting these assembly constraints indicates printing the holes with axes in vertical position and taking into account that the holes will be manufactured with a smaller diameter than the nominal value [26]. However, the vertical build orientation makes the adapter weaker in terms of tensile strength. During the robot working cycle, the adapter is mostly subjected to tensile and less to compressive or shear stresses, therefore the load should be distributed along the layers instead of across layers [27]. Therefore, it was decided to print the part horizontally (adapter holes with axes in horizontal plane) as a first compromise between the holes accuracy and the adapter tensile performance. It should be noted also that in the chosen build orientation, the printing time was 1 h and 41 minutes longer and implied manufacturing and then removing support structures. However, in the requirements priority list, the adapter mechanical performance was ranked first, followed by the holes accuracy and then by the printing time/cost.

The straightforward solution to reduce the manufacturing time in 3DP is decreasing the infill percentage and the number of shells/contours. However, this is done at the cost of lowering the mechanical strength. Despite the extensive experimental work in the field [9-10], there are not enough data for estimating the combined impact of these parameters on the mechanical behavior of parts with complex geometry. Moreover, the experimental tests presented in literature do not tackle the problem of 3D-printed parts mechanical strength within an assembly subjected to combinations of loads, instead focusing on specimens. Thus, a trial and error process was the only solution for finding the settings that produce a reliable adapter, the engineers experience and research studies, acting as filters for reducing the number of trials.

Based on the literature data [28], the effect of infill density over the tensile strength is more significant for infills smaller than 70%, the improvement of this mechanical property being less relevant as the density increases over this density value. Obviously, the maximum tensile strength is obtained for 100% density with the disadvantages of a longer printing time and stiffness increase, not of these being desirable for this adapter. Thus, the next decision was to manufacture the adapters with infill densities of 40%, 50% and 60%. The following question to answer was related to the infill pattern and the number of shells. For analyzing the effect of different values of these process parameters on the estimated printing time and material consumption, the 3D printer slicing software was used. It supported the elimination of many of the available infill patterns, grid and gyroid being finally kept as options.

An adapter in design variant 1 was built with grid 40% infill and three shells, and it failed after two days of use (Table 2). Then the adapter was modified to design variant 2 and the process parameters values were also modified (table 2). Gyroid pattern was used for 3DP all the following adapters (a research study indicating that it offers the best strength-weight ratio [29]), although the printing time was longer at the same infill density than for the grid pattern.

Table 2

Parameter settings combinations for the 3D-printed adapters

Adapter	Design	Infill pattern	Infill density	No. of shells	Print time	Usage time
1	Variant 1	grid	40%	3	29h 35min	1 day
2	Variant 2	gyroid	50%	3	35h53min	90 days
3	Variant 2	gyroid	60%	3	40h 11min	3 weeks
4	Variant 2	gyroid	40%	6	26h 25min	on going

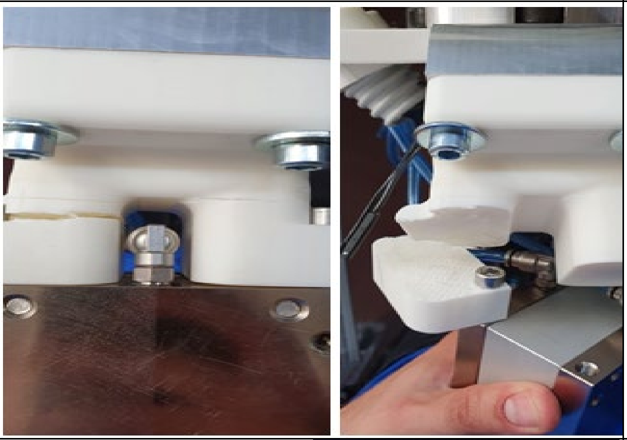
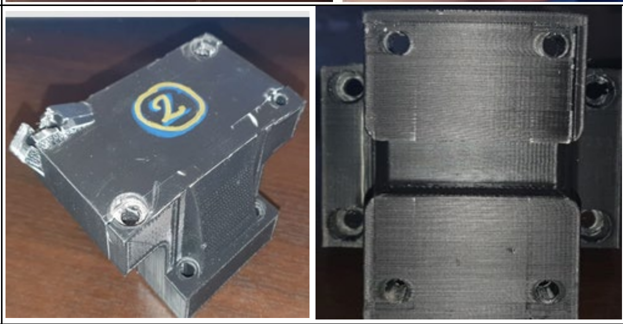
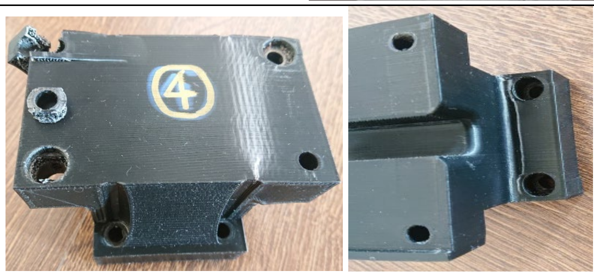
Initially, the number of shells was set to 3 as a compromise between the printing time and the mechanical strength [24]. However, after the second adapter failed around the fixation holes, the density was increased at 60% (adapter 3), while at the next decision the number of shells was increased to 6 and the density was decreased at 40% (adapter 4) for reducing the printing time.

The solution of drilling the holes was not considered despite the advantage of a better accuracy as literature on open hole testing shows the importance of reinforcements around holes for a good mechanical strength [30]. At the date of writing this paper, adapter 4 was in function for more than seven months.

Table 3 includes selected images of the adapters’ breakages occurred during robot operations, as well as the lists of the decisions made after analyzing each failure.

Table 3

Adapters' failures

Details	Failures images	Failure occurrences	Decisions
Adapter 1 - design 1		At a payload of 15 kg	• Changing the design by adding reinforcement • Changing the infill type to gyroid • Increasing the infill density • Keeping the same number of shells
Adapter 2 - design 2		At a payload of 40 kg	• Increasing infill density • Keeping the same number of shells
Adapter 3 - design 2		Due to operator error; impact with the lathe	• Decreasing the infill density • Increasing the number of shells

5. Conclusions and further research

Currently, designing and 3D printing parts for functional applications require a trial and error process sustained by engineers experience and data from scientific literature. Analyzing the failures during part's usage and accordingly taking decisions to improve the design and/or process parameter settings are the mandatory steps to follow. It should be noted though that this approach can be time consuming and expensive because of the sacrificial parts, and it can provide a workable result, but not necessarily the optimal result.

Disseminating the good practice in the field is beneficial for reducing the iterations associated to this development process of the 3D-printed parts. This is even more important as most of the studies are focused on assessing the process parameters influence on mechanical performances of testing specimens, and not on functional parts. The complex dependence between 3DP process parameters and prints' mechanical behavior often produces unpredictable results, while the current unavailability of a computer-aided tool based on FEA fully adapted to the material extrusion AM process is adding difficulties to the process.

In the context, this paper documented the development process of a 3D-printed adapter for a robotic gripper describing how different design and manufacturing decisions were made to deliver the required outcome. Trade-offs were needed between adapter's strength, stiffness, and printing time/cost. Two variants of designs were tested, for the second design three versions of adapters 3D-printed with different process parameters settings being implemented in the robotic cell. The experienced acquired during the adapter implementation in the first robotic cell was used in other applications with similar functionality.

Further research will be focused on studying the effect of reducing infill density (with the purpose of reducing printing time and adapter mass) while strengthening the zones around the hole by applying the concept of adaptive filling strategy within the 3D-printed parts.

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