*Production engineering, production process,
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6 DETERMINATION OF SELECTED CHARACTERISTICS OF THE ADDITIVE MANUFACTURING PROCESS ON THE EXAMPLE OF TESTING THE PROPERTIES OF SCREWS PRODUCED IN THE FDM TECHNOLOGY

Abstract

Additive manufacturing is still a relatively young production process, but the ever-growing number of additive manufacturing applications in the engineering industry proves the forecasted dynamic development of this process over the coming years. The main purpose of the article is to study the mechanical properties of screws produced in the additive manufacturing process. In addition, during the research, the specific objective was to determine the selected characteristics of the additive manufacturing process, such as the relationship between the production time and layer thickness, as well as the relationship between the production time and filament consumption on the filling value. Four different materials were used for testing - PLA, ABS, ASA and PET-G. In addition, the screws had different sizes and thread lengths. In the analysis of the current state of knowledge in the field of the subject, the application areas of additive manufacturing, important from the point of view of production engineering, were also defined.

6.1. INTRODUCTION

Empirical research conducted in 2019 among 250 Polish manufacturing companies from the metal and automotive industries shows that almost half of the respondents use additive manufacturing technology, and more than half are interested in implementing it. According to the empirical research results cited above, companies from the automotive industry use additive manufacturing processes mainly for the production of technical devices (21.6%) and prototyping (23.2%) [1].

Defining areas of knowledge about additive manufacturing technologies in manufacturing companies is widely described in the literature. Qi et al. described in the work the acquisition and analysis of data on the mutual influence of the

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geometric design and process parameters in order to meet the requirements of the specificity of additive manufacturing technology using knowledge formalization tools based, among others, on descriptive logic [2]. Greek researchers from the University of Patar, on the other hand, raise in their research the aspect of stage analysis and selection of the appropriate additive manufacturing process for the company's needs [3]. The use of additive manufacturing technology for rapid prototyping of spray nozzles, together with research procedures to check the suitability of this technology in their work, was presented by Bałaga et al. [4]. Planning of additive manufacturing processes and defining the order of tasks in the processes, as well as the flow of messages using, among others, the Pareto diagram or the Ishikawa diagram, was described by Liang [5]. Caban et al. described the use of additive manufacturing in the automotive industry on the example of designing new elements and parts of vehicles [6].

3D printing, apart from the machine industry, is also widely used in medicine [7]. These applications certainly include personalized implants and prostheses, models that allow surgeons to simulate surgery before it is performed, surgical instruments, hearing aids and orthoses.

Oyesola et al. performed data analysis to leverage an integrated additive manufacturing process chain, from component design to pretreatment, manufacturing (laser unit construction), finishing and finished parts, using multicriteria decision making, additive manufacturing design, among others or multicriteria optimization [8]. Other researchers use Bayesian networks to gather knowledge about the demand and use of additive manufacturing technology in a manufacturing company, and to support managers in making decisions about implementing additive manufacturing technology [9]. Sanfilippo et al. proposed the use of a skeletal structure to organize data from the additive manufacturing process and automatically analyze expert knowledge for data validation, using available algorithms and applications to support decision making [10]. Hertlein et al. analyzed the relationship between the parameters of the additive manufacturing process and various parts quality features [11]. Other researchers, however, conducted an analysis of operational parameters affecting the production process in additive manufacturing and the quality of components produced by 3D printing technology, using digital models and numerical modeling for the analysis [12].

6.2. DETERMINATION OF SELECTED CHARACTERISTICS OF THE ADDITIVE MANUFACTURING PROCESS

6.2.1. Areas of application of additive manufacturing technology

It is possible to use machine learning methods to analyze large data sets, including deep learning, or heuristic algorithms for data classification and predicting the additive manufacturing process. Improved information from data analysis of 3D printing processes can also support the design of better and more efficient products [13].

In addition, since technologies based on big data sets and 3D printing have been selected among the nine pillars of technological advancement in Industry 4.0 [14], it can be expected that the combination of both technologies will have a significant impact on the development of the industry in the future. Additive manufacturing at its core is a highly revolutionary technology that has developed over the years into a versatile technological arena. Materials currently used for additive manufacturing include thermoplastics, ceramics, graphenebased materials and metal. 3D printing can change the industry and improve the production process. Its implementation will speed up production while reducing costs. The importance of consumer demand and its impact on production will be greater. Consumers will have a greater voice in the final product and will be able to demand that it would be produced according to their preferences. Factories would be established close to consumers, which would lower transportation costs. The implementation of 3D printing innovations in the assembly industry also has several disadvantages, for example, the use of 3D production methodology reduces the physical effort or labor involved in the production process, which has a significant impact on the economies of countries that depend on a huge number of lowcapacity jobs [15]. Selected 3D printing technologies along with the area of application and their advantages and disadvantages are presented in tabular form below (Tab. 6.1.).

Tab. 6.1. Selected 3D printing technologies along with the selected area of application, advantages and disadvantages [own elaboration]

3D printing technology	Selected area of application	Disadvantages	Advantages	Source
SLA - *Stereolitography*	Designer models in the clothing industry, Optics and transparent covers;	Unprofitable, Excessive curing of layers, scanned line shape;	Good production speed, Good quality;	[16]
Polyjet	Form and fit testing and product presentation, Prototyping complex parts;	low-strength material, Requires filtration after processing, High porosity;	Multi-material printing, Smooth outer layer, Full color objects, Wide selection of materials;	[17]
LOM - *Laminated object manufacturing*	Creating architectural models, Rapid prototyping techniques;	Cube removal problems, The material should be in sheet form only;	High quality final product, Economic;	[17]
DMLS - *Direct metal laser sintering*	Rocket engine combustion chamber;	Low-volume production, Only a limited size of the product can be produced;	Freedom to design metal end products, Complex geometries, High quality;	[18]
EBM - *Electron-beam melting*	Titanium aluminides for aerospace and automotive applications;	Negative pressure is required Extremely expensive;	No preheating required An electron beam is used;	[19]

SLS - *Selective Laser Sintering*	Biomedical molding, Dental implants, Aviation and military components;	Powder handling and recycling;	It can produce metal and functional components with complex geometry, Precise;	[20]
FDM - *Fusion deposition modeling*	Aviation prototyping, BioMedical, Automotive, Instrument and accessory development;	Limited part resolution, rough finish;	Affordable extrusion machine, A wide range of available materials, Multi-material printing;	[18]
LENS - *Laser engineered net shaping*	Medicine, Aircraft;	A balance must be struck between surface quality and speed, Requires post-processing;	Can be used to repair damaged or worn parts, Functionally graded material printing;	[16]
SLM - *Selective laser melting*	Conformal channels in heat exchangers, Biocompatible metal frame for dentures;	Preheating is required Post-processing is needed for sand removal;	No supporting structures are required, No need for auxiliary materials;	[18]

Additive manufacturing technologies are now more and more often used in manufacturing companies, especially due to the need of shortening the time needed to introduce a new product to the market [9]. Additive manufacturing technologies are used in the area of design and construction, especially in manufacturing companies from the automotive, aerospace, military and metal industries [21].
Based on the analysis of the literature [22-24], the characteristics of the additive manufacturing technologies can be divided into:

- Automotive industry sector:
  - Production processes of machine parts and devices made of plastic and metal, including precise mechanical parts and subassemblies,
  - Production processes of functional prototypes and cooperating mechanisms,
  - Manufacturing processes in models used for stress testing and modelling.
- Metal industry sector:
  - Prototyping and modeling processes,
  - Production processes of injection molds, casting moulds, structures and other elements with complex geometry or requiring high mechanical properties, the production of which would not often be possible using casting technologies,
  - Repair and regeneration processes for complex damaged metal parts.

6.2.2. FDM Technology

In the further part of the work, the focus was on the FDM technology. This technology uses thermoplastics (plastics) in the additive manufacturing process, which are used to properly form the geometry at high temperatures. Models created with this technology are created by applying successive layers of semi-liquid material that is extruded from a heated nozzle. The material is in the form of a monofilament with a constant diameter (usually $Ø = 1.75$ mm $\vee$ $Ø = 2.85$ mm), which is wound on a spool. This material is defined as a filament.

The technology discussed above was patented by Crump in 1989. The device operating in accordance with the FDM method is equipped with a movable filament dispensing head that solidifies at a certain temperature and a base that moves relative to the head in the "X", "Y" and "Z" axes in predetermined directions, creating three-dimensional objects. The entire procedure can be carried out using computer-aided design and computer-aided manufacturing. It is currently the most common method of additive manufacturing in manufacturing companies. It gained its popularity, among others, due to the relatively simple construction of the devices and the expiry of the FDM patent discussed above.

The previously described 3D printing technology, FDM, which was used as an example of the production process in this work, is currently the most common method of manufacturing parts using additive manufacturing, which is influenced, among others, by its simplicity along with relatively cheap machines, with the possibility of their modification in for higher efficiency and better print quality [25]. In this aspect, additive manufacturing can be used to produce finished products, even taking into account the inferior parameters of prototype products. Analyzing the current state of knowledge [26], it was found that the print quality is affected by many characteristics of the additive manufacturing process depending on:

- machinery,
- human,
- technology,
- surroundings,
- material.

Currently, finished products manufactured in the additive manufacturing process, which are three-dimensional objects, are made of thermoplastics. In some cases, filaments are used in addition to thermoplastic, contain additional components (including glass fiber scraps, graphene or rubber microspheres), which directly translates into the properties of the manufactured products, which, according to Kaczmarska and Michta, can be treated as multi-material on a micro scale. Through additive manufacturing, other types of multi-material products can also be produced by encasing parts that were previously made of other materials (including metal or wood) with thermoplastic [27].

The selection of appropriate parameters in the additive manufacturing process is necessary in order to obtain a properly made product, an example of which is the

M8 screw shown in the drawing (fig. 6.2.). Incorrect determination and selection of characteristics for the additive manufacturing process may result in defective products, where below in the figure (fig. 6.1., for example, an M8 screw with a melted ASA filament in the final phase of production is shown.

Fig. 6.1. M8 screw made of ASA filament in FDM technology with the selection of incorrect print parameters [own elaboration]

Fig. 6.2. M8 x 30 mm screw made of ASA filament in FDM technology with correctly determined print characteristics [own elaboration]

In the additive manufacturing process, it is also possible to modify many parameters, such as layer height, print speed or degree of infill. When analyzing 3D prints in the FDM technology, the layer height can be defined as the distance that is covered by the working table in the Z axle after applying one layer of the manufactured product. In terms of value, the layer height can be defined in the software used to divide the product model into individual layers, currently in the vast majority this value ranges from 0.05 [mm] to 0.4 [mm] for machines available on the market. An important characteristic in the additive manufacturing process is also the diameter of the nozzle opening through which the thermoplastic is extruded, as noted in [28] that in the case of using a nozzle with a diameter of 0.4 [mm], the head must cover three times longer distance during the process than in the case of using a nozzle with a diameter of 1 [mm], as shown in the figure below (fig. 6.3.).

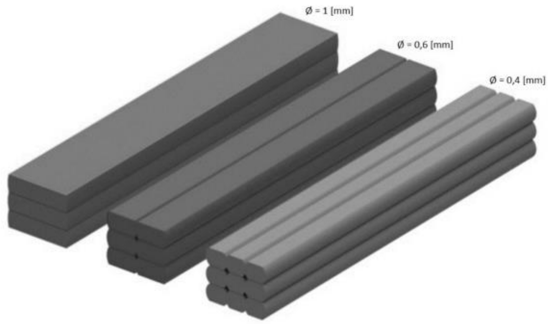

Fig. 6.3. Influence of the nozzle diameter on the number of passes made on the base [28]

6.3. TESTING THE MECHANICAL PROPERTIES OF SCREWS PRODUCED IN FDM TECHNOLOGY

6.3.1. The FDM process parameters

It is also worth noting that the amount of filament used during the manufacturing process of the incremental filament depends on the characteristics determining the layer height - with the decrease in the value of the layer height, the amount of used filament increases, intended for the production of the finished product [29]. In addition, the characteristics defining the thickness of the layer are shown in the figure below (fig. 6.4.), from which it can be concluded that with the increase of the layer height, the amount of filament needed to make the finished product is reduced, which also has a direct impact on the efficiency of the process in line with the savings criterion.

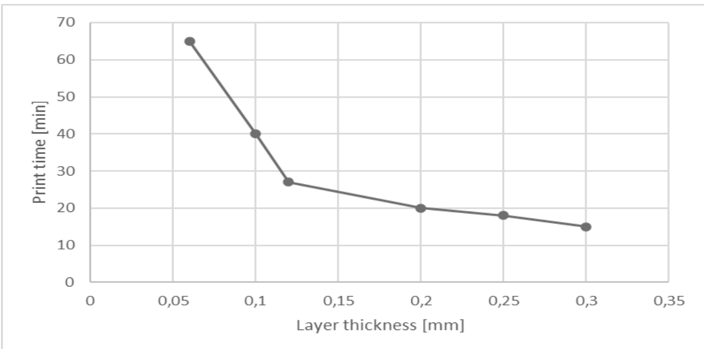

Fig. 6.4. The dependence of the printing time on the thickness of the layer [own elaboration]

Another characteristic of additive manufacturing is the degree of filling, which is expressed as a percentage. This is a parameter that is directly responsible for the amount of filament filling the interior of the manufactured product. The filling value of 100% is used in the production of solid products, while the filling value of 0% is used for internally hollow products, the most frequently used filling value is around 20%, which allows for a relatively short production time of the product itself on the machine, and affects the savings related to the consumption of the filament, which directly affects the increase in the efficiency of the process itself, by reducing the costs incurred in relation to the effects obtained. To sum up the modification of this parameter affects the possibility of obtaining finished products that will be diametrically different from each other, starting from a fully filled printout, to a model containing only side walls.

Loncierz et al. in their research on the degree of filling of objects printed in FDM technology, also showed that the modulus of elasticity and tensile strength show similar tendencies. They noted higher values for products with 80% filling, where an increase of 70% was recorded for measurements made for Young's modulus and 85% for tensile strength measurements. The finished product with 80% filling obtained results in tests close to the values measured for products with 100% filling, so the researchers assumed that by setting the degree of filling at 100%, the measured values could correspond to those that would be possible in measurements for finished products with a solid internal structure [29].

The graphs below show the change in the filament consumption value (fig. 5) and the change in the print spell (fig. 6.6.) depending on the change in the filling density of the finished product in the additive manufacturing process. Based on the graphs below, it can be seen that with the increase in the degree of filling, both the production time of the product and the amount of filament needed for its production increase.

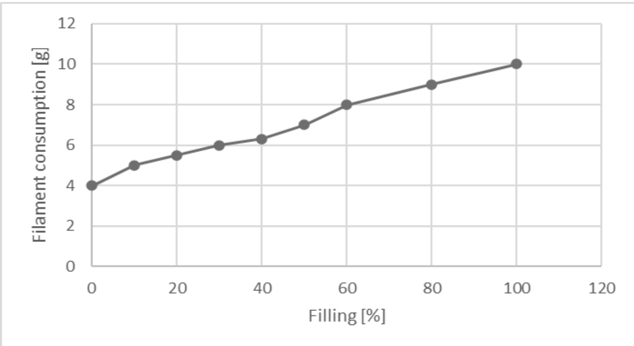

Fig. 6.5. Dependence of material consumption on filling density [own elaboration]

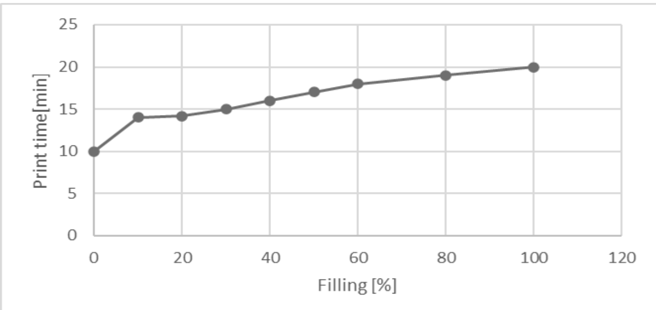

Fig. 6.6. The dependence of the printing time on the filling density [own elaboration]

Another group of additive manufacturing characteristics may be parameters that are responsible for defining the supports that will be responsible for the correct production of the finished product, if it is composed of elements that do not have support in the design itself - for example, it can be a protruding handle. It is assumed that each protruding element at an angle of less than 45° should be supported in order to avoid defective products, except for bridges - where the manufactured element is fixed between two supports. But then there is a risk stretching of the filament, which has not yet cooled down, under the influence of gravity, depending on the length of the bridge in question. Among the characteristics defining supports in additive manufacturing, the following can be distinguished [6]:

- option to enable / disable supports,
- the limit value of the angle of elements for which supports will be generated,
- the limit value of the length of the bridge, which does not require additional support along its entire length,
- the minimum distance between the supports and the side edges of the manufactured product,
- minimum distance between the supports and the supported layer,
- support spacing density.

An important parameter for the additive manufacturing process is also the printing speed, which can be determined at the code generation stage, where it is possible to determine:

- filling printing speed,
- printing speed of element side walls
- head movement speed during the additive manufacturing process,
- printing speed of the first layer,
- printing speed of the internal walls of the element.

The test is aimed at measuring the breaking force of the frictional connection between the screw and the ankle (fixed in a vice), as well as the force needed to damage the threaded connection (broken thread of the screw/ankle, broken core of the screw). The tested elements were designed and manufactured using additive technology from the available filaments: ASA, ABS, PLA and PET-G. Testing the breaking force of the frictional connection between the screw and the ankle and the force needed to damage the threaded connection is an important element of assessing the strength and reliability of the structure. The breaking force of a frictional connection measures the maximum force that can be applied to the connection when it is disconnected to damage the thread or core of the bolt.

In order to perform the test, the screw and the ankle should be clamped in a vice and, using a dedicated tool (e.g. a torque wrench), measure the force needed to disconnect the frictional connection or damage the threaded connection. Multiple tests can also be performed to verify that the force required to fail a threaded connection varies during load cycles.

The results of such a test make it possible to assess the strength and reliability of the connection and to select the appropriate design and material parameters for a specific application. They also allow you to compare different construction solutions and choose the optimal one.

The course of the test is presented below, where after modeling the screws (fig. 6.7.), the manufactured elements (fig. 6.10.) were tested on a test stand equipped with a vice (fig. 6.9.) and a torque wrench along with a calibration certificate.

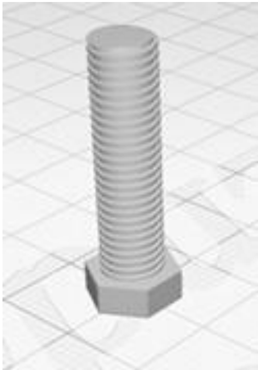
Fig. 6.7. M6 srew model x 30mm
[own elaboration]

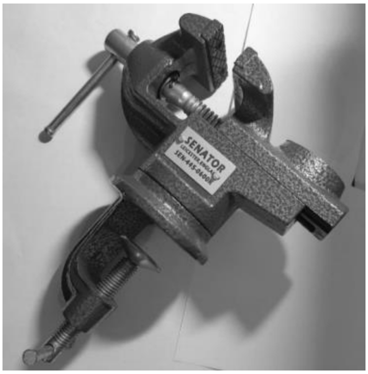

Fig. 6.8. Holder SENATOR
[own elaboration]

The method of attaching the cubes and screws is shown in the figure below (fig. 6.9.).

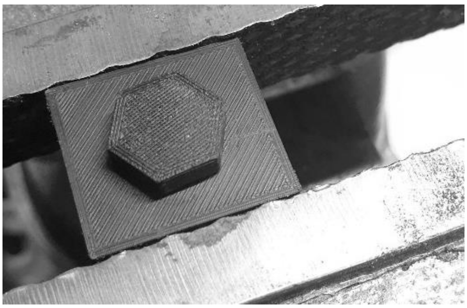
Fig. 6.9. A screw placed in a cube made of ASA filament [own elaboration]

Fig. 6.10. Bolts prepared for testing
[own elaboration]

Below there are pictures of damaged screws during the tests with their structure visible, respec-tively for PLA (fig. 6.11.), ABS (fig. 6.12.), ASA (fig. 6.13.) and PET-G (fig. 6.14.) filaments.

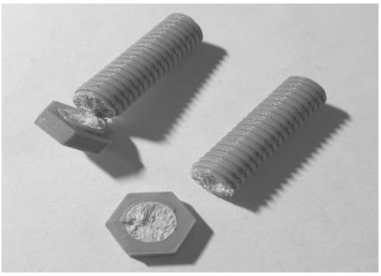

Fig. 6.11. Damaged screws made of PLA [own elaboration]

Fig. 6.12. Damaged screws made of ABS [own elaboration]

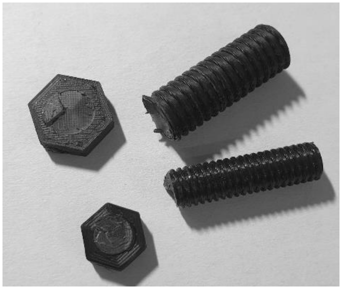

Fig. 6.13. Damaged screws made of ASA [own elaboration]

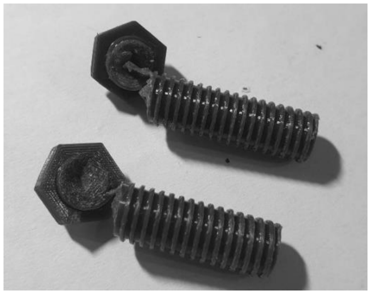

Fig. 6.14. Damaged screws made of PET-G [own elaboration]

The results of the measurements are presented in the table (Tab. 6.2.).

Tab. 6.2. The results of the measurements [own elaboration]

Screw type / material	Tightening torque at which the screw was damaged [Nm]	Average tightening torque [Nm]	Screw type / material	Tightening torque at which the screw was damaged [Nm]	Average tightening torque [Nm]
M6 x 25 mm / ASA	0,9	0,88	M6 x 30 mm / ASA	1	1,12
	0,8			0,9	
	0,9			1,4	
	0,9			1	
	0,9			1,3	
M6 x 25 mm / PLA	3,2	3,16	M6 x 30 mm / PLA	3,5	3,3
	3,1			3,4	
	3,1			2,9	
	3,1			3,4	
	3,3			3,3	

M6 x 25 mm / ABS	0,9	0,76	M6 x 30 mm / ABS	0,8	0,76
	0,9			0,9	
	0,6			0,8	
	0,7			0,8	
	0,7			0,5	
M6 x 25 mm PET-G	1	0,98	M6 x 30 mm PET-G	1,2	1,06
	1,1			1,2	
	1,2			1,2	
	0,7			0,7	
	0,9			1	
Screw type / material	Tightening torque at which the screw was damaged [Nm]	Average tightening torque [Nm]	Screw type / material	Tightening torque at which the screw was damaged [Nm]	Average tightening torque [Nm]
M8 x 30 mm / ASA	2,5	2,34	M8 x 25 mm / ASA	1,5	2,02
	2,3			2,1	
	2,4			2	
	2,3			2,1	
	2,2			2,4	
M8 x 30 mm / PLA	5,7	5,58	M8 x 25 mm / PLA	5,8	5,7
	5,6			5,8	
	5,2			6	
	5,5			5,2	
	5,9			5,7	
M8 x 30 mm / ABS	1,1	1,34	M8 x 25 mm / ABS	1,1	1,36
	1,4			1,5	
	1,4			1,4	
	1,5			1,4	
	1,3			1,4	
M8 x 30 mm PET-G	3,2	3,02	M8 x 25 mm PET-G	1,6	1,64
	3			1,8	
	3,1			1,9	
	3,1			1,5	
	2,7			1,4	

6.3.2. Results and discussion

The measurement results allow to assess the strength and reliability of individual types of screws, depending on the material from which they were made and their size. They also allow you to compare various design solutions and choose the optimal ones for a specific application. Below, the results are presented in a graphical form (fig. 6.15. – 6.22.).

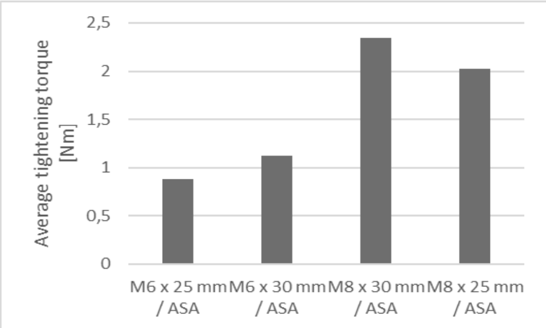

Fig. 6.15. The results obtained for screws made of ASA filament [own elaboration]

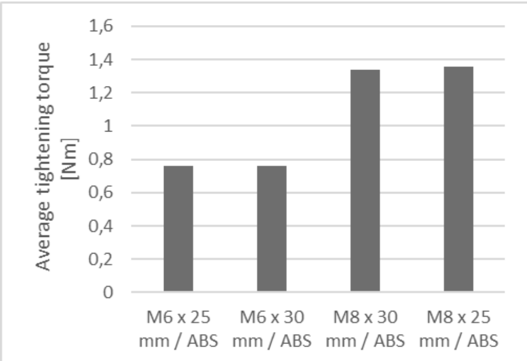

Fig. 6.16. The results obtained for screws made of ABS filament [own elaboration]

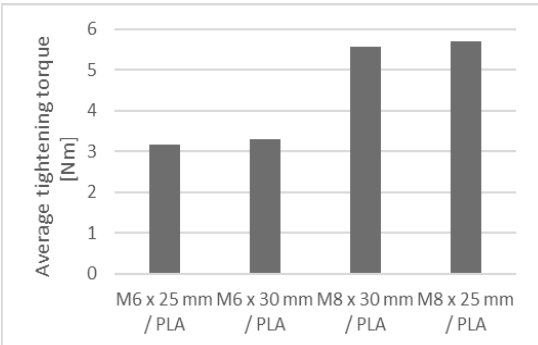

Fig. 6.17. The results obtained for screws made of PLA filament [own elaboration]

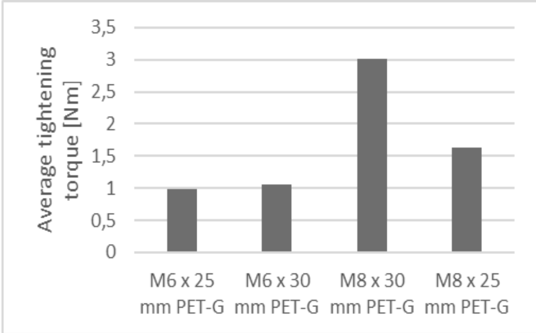

Fig. 6.18. The results obtained for screws made of PET-G filament [own elaboration]

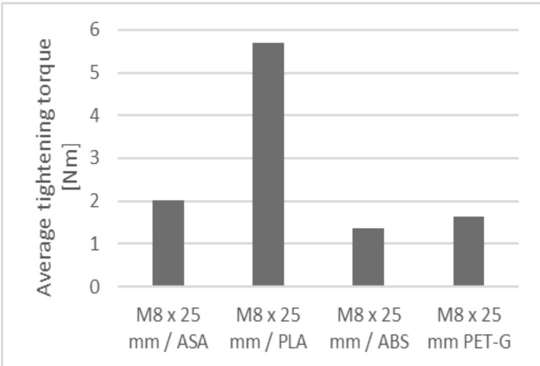

Fig. 6.19. The results obtained for screws M8 x 25 mm [own elaboration]

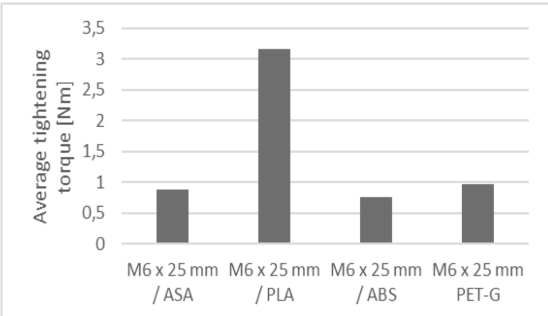

Fig. 6.20. The results obtained for screws M6 x 25 mm [own elaboration]

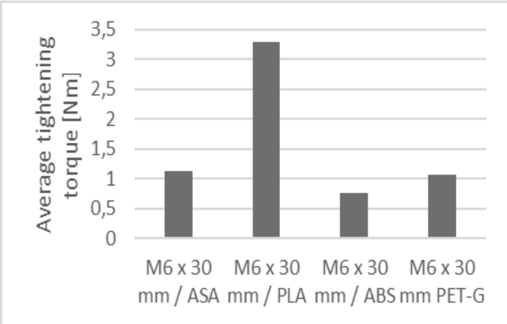

Fig. 6.21. The results obtained for screws M6 x 30 mm [own elaboration]

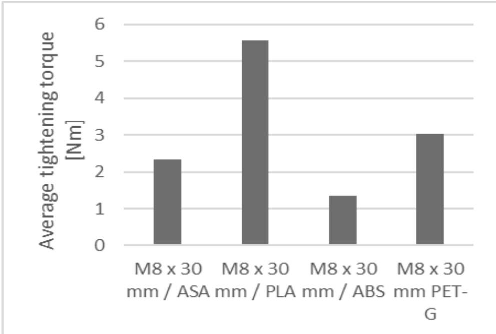

Fig. 6.22. The results obtained for screws M8 x 30 mm [own elaboration]

Directly after performing the above sample tests, it can be concluded that screws made of PLA withstand the highest tightening torque. It is also worth noting that the production of threaded elements in the additive manufacturing process requires an appropriate approach already at the modeling stage, the 3D model should take into account the appropriate clearances for the threaded connection, which depend on the arrangement of the model relative to the machine coordinate system. In this case, the vertical arrangement - i.e. the one where the axis of rotation is parallel to the vertical axis of the machine is the most advantageous position due to the accuracy of the thread mapping. The printed models withstand relatively low torques, but can be used in the fastening of small-sized covers or diaphragms.

6.4. CONCLUSION

The selection of appropriate parameters in the additive manufacturing process is necessary to obtain a properly made product. In the preparation of the additive manufacturing process, apart from the possibility of determining the value of the filling density, it is also possible to define filling patterns (among others: grid, diamond or honeycomb). The filling pattern of the manufactured object does not have a significant effect on the amount of filament used or the time of the printout itself.

If the strength of manufactured products is a priority, it would be appropriate to select the highest value of the filling density. A correlation was also noted between the degree of filling and the quality of the outer side surfaces, showing that increasing the degree of filling also increases the quality of the side surface. On the other hand, it is worth noting that the use of 0% infill may negatively affect the print quality, making it necessary to reprint. When choosing the right degree of filling, it is necessary to pay attention to the shape, purpose and conditions in which the finished product is to be used. The surfaces in the printed element that are parallel to the machine's working surface can be significantly distorted and in many cases broken when using 0% infill.

The method of manufacturing threaded connection elements using 3D printing involves certain technological difficulties. In most cases, threaded connections are based on standardized design principles and the use of standardized fasteners, thanks to which this type of connection is relatively cheap and widely used. It is worth noting here that all screws are made with 100% filling. To sum up, PLA will be the best choice when it comes to filament intended for the production of elements in the field of screw connections. In further research aimed at determining the characteristics of the additive manufacturing process, the authors intend to examine also other elements of machine parts. The obtained results will be used at a later stage to build knowledge bases in order to improve the efficiency of the production process of machine parts.

The research has demonstrated a correlation between production time, layer thickness, and filament consumption. Subsequent studies can focus on optimizing these parameters to achieve optimal mechanical properties for various sizes of screws and types of materials. Further investigations are anticipated to involve verification under real operational conditions. Future research may center on comparing the mechanical properties of screws produced using 3D printing technology with traditional manufacturing methods such as machining and forging. Such a comparison would provide a better understanding of the advantages and limitations of 3D printing in the context of mechanical component production. Despite promising prospects, there is a need for additional research to fully comprehend the potential and constraints of 3D printing technology in the production of mechanical components.

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