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Influence of Operating Fluids on Mechanical Properties of Parts Produced by Additive Manufacturing

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Abstract:

The article examines material extrusion – one of the most accessible additive manufacturing technologies – as a viable option for transforming the operational logistics system supporting temporary repairs of ground military equipment. Nowadays, in many armies, additive manufacturing is starting to act as a game changer in the field of military logistics and material supply. At this stage, the research focused mainly on assessing chemical compatibility and the effect of operating fluids on changing the mechanical properties of materials. Based on the evaluation of the results, the chemical compatibility of the materials and operating fluids most commonly used in the field of ground military equipment was determined. The final part of the work defines the basic prerequisites for the design of components manufactured in this way, including the example given.

Keywords:

chemical compatibility, additive manufacturing, material extrusion, temporary repair, design optimization

1 Introduction

Additive manufacturing, or additive manufacturing technology, is a collective name for a relatively disparate set of manufacturing technologies, the link between which, in contrast to conventional manufacturing technologies, such as chip machining, is the gradual addition of material to clearly defined coordinates of the built space to create a finished three-dimensional part, with different mechanical properties, accuracy and surface quality depending on the specific technology [1].

In the professional literature, additive manufacturing processes are classified in various ways, depending on factors such as the type of material, state of fusion, mate-

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rial feedstock, method of material distribution, or source of energy for fusion [1–3]. In addition, it is very difficult to compile a valid overview of all technologies falling into the general category of additive manufacturing, taking into account the fact that these technologies are currently developing rapidly and new processes that meet the basic assumption of additive manufacturing, i.e. the gradual addition of material to the product are emerging [4].

The basic and the friendliest overview shown in Fig. 1 can be compiled assuming that we generally divide additive manufacturing based on whether it is suitable for production from metallic and non-metallic materials. This division will then be filled with an overview of individual manufacturing processes using the processes listed in ISO/ASTM 52900:2021 Additive manufacturing – General principles – Fundamentals and vocabulary [5]. For clarity, the technologies are first sorted according to the type of material, then according to the form of the production material and the type of energy. Subsequently, processes that were not included in the 2021 standard are categorized as a part of the wire and arc additive manufacturing (WAAM) process [6].

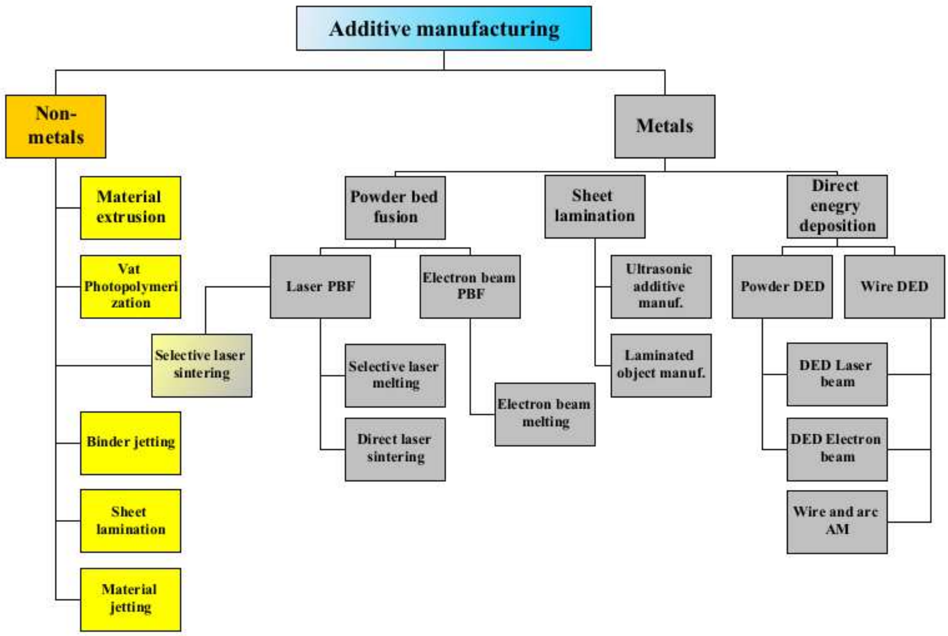

Fig. 1 Processes of additive manufacturing

The disadvantage of the given overview is that some processes falling into the category of selective laser sintering are included to produce both metallic and non-metallic materials, even though the procedures and production equipment are diametrically different [7, 8].

All these technologies are currently becoming an integral part of the production process across industries. Initially, these technologies began to be used mainly in the initial stages of industrial product development but are now also being used in more advanced stages of mass production.

In the automotive industry, additive manufacturing is used not only to produce fixtures intended for manual assembly but also for the production of fixtures intended for mechanized mass production, in some cases even for the production of final parts intended for assembly on a commercially available product [9–11].

Due to the advantages associated with the above technologies, additive manufacturing is currently being introduced to various degrees into the logistics supply of individual armies, both at the national and international levels [12]. Individual armies are introducing specialized centers and workshops into their structures to address the issue of additive manufacturing to produce training aids, replacement parts for military equipment, or individual equipment. Examples include the WiWeb center of the Armed Forces of the Federal Republic of Germany [13] or the Rock Island Arsenal – Joint Manufacturing and Technology Center of the United States Army [14]. The armies are also addressing the development of mobile workshops that would be deployable abroad. The most commonly used technology for these usual container solutions is material extrusion (MEX) to produce polymer materials [15]. For this reason, special attention should be paid to the MEX process, because it can be used even outside sophisticated production facilities.

This means that satisfactory replicability of the print quality can be ensured in field conditions. Moreover, in this technology there are no demanding requirements in terms of handling the production material from the point of view of safety (health-hazardous fine dust in powder technologies, also explosive in the case of metal materials). The technology is also quite resistant to possible contamination of material, especially by moisture when handled in unsuitable conditions. The production material is usually in the form of a continuous string wound on spools. The operation of the production equipment and subsequent post-processing of the products is also much less demanding compared to most other technologies. This makes this technology advantageous for use in foreign military operations, i.e., where there is an immediate need for a part and its production would be of the greatest importance in terms of reducing logistical delays.

For the successful application of additive manufacturing process for a specific application, in addition to the design of a suitable topology and correct orientation on the printing substrate, it is necessary to choose a suitable material so that the final component can withstand all the loading influences that affect it in operation. Data sheets are issued for individual materials, where mechanical properties are defined. However, in addition to the mechanical stress, temperature and other degrading influences affect components of ground military equipment. These are mainly operating fluids. Manufacturers usually issue chemical resistance tables for individual polymeric materials, but these usually define chemical resistance without quantifiable data, using the division of resistance into four groups: excellent, good, fair, and poor. Based on this categorization, it is not possible to effectively decide whether a selected material will withstand its exposure for the required period. The main objective of this research is to define the chemical resistance of materials used in polymer manufacturing for use in ground military equipment, with regard to their chemical exposure to operating fluids.

2 Material Extrusion

This is the most accessible and widely used additive manufacturing process at both the amateur and professional levels. Some manufacturers also use the trade names Fused Filament Fabrication (FFF) [6] and Fused Deposition Modeling (FDM) [7].

In this technology, the material is applied layer by layer onto a usually heated printing substrate (Fig. 2). The production material in the form of a string or pellets is fed to the print head, extruder, from which the name comes: material extrusion, which consists of a feed mechanism and a hot end with a nominal diameter that corresponds to the thickness of the applied layer in the *z*-axis and in the y-axis. In the hot end, the material is melted and deposited onto the printing substrate or onto a previously printed section of the part. This process forms both the external contours of the product and its internal structure (infill). The infill may be solid; however, to reduce production time and material consumption, a grid-like structure is more commonly used. The density of this structure can be adjusted in the printing preparation software according to the expected mechanical loads acting on the part [16]. Of course, there are more parameters that can be changed during production, depending on the production equipment used. An overview of all changeable printing parameters is given in Tab. 1.

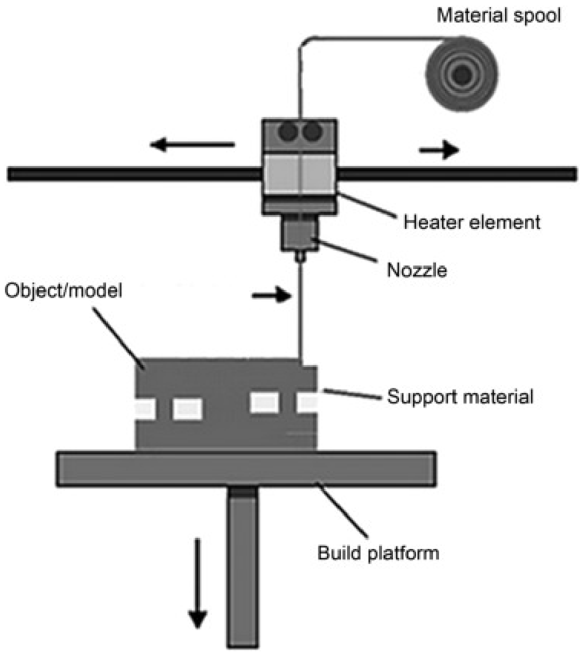

Fig. 2 Schematic diagram of MEX process [17]

2.1 Recently Used Materials

The most commonly used materials in this process must be divided into those that can be processed on desktop devices and those that can be processed on industrial devices. They differ in terms of usability, especially in terms of achievable mechanical properties and temperature resistance, and in terms of production requirements, especially depending on the hot end temperature, the temperature of the built chamber and the temperature of the printing bed. For the purposes of this research, a set of commonly processed materials was used, not requiring a specific production procedure or demanding post-processing. The main reason is the assumption of using equipment suitable for operational use that is capable to work with this material. A precise list of materials is contained in chapter 3.

Tab. 1 Generally adjustable parameters of MEX process [18, 19]

Parameter	Description
Hot end temperature	The hot end temperature is set depending on the printed material.
Scan speed	The speed at which the hot end moves across the built chamber and the associated material (filament) feed rate.
Nozzle diameter	Adjustable by changing the nozzle. Commonly used sizes – 0.2 (0.25), 0.4 and 0.6 mm.
Built chamber temperature	In some more expensive devices, it is possible to adjust the pre-heating of the built chamber to avoid volume changes in the materials and related defects.
Built plate temperature	For devices with a heated print bed.
Retraction	Retraction is the temporary rewinding of filament back into the extruder during transitions between different sections of the printed object. Its purpose is to prevent unwanted material oozing from the printer nozzle during non-printing movements, thereby reducing the occurrence of surface defects in the final product.
Printing temperature	The temperature of the built chamber and/or built plate.

2.2 Advantages, Disadvantages and Limitations of Technology

Compared to other production technologies, MEX is the simplest and most user-friendly additive manufacturing process, which would be suitable even for lower levels of logistics support. Both affordable desktop printers and advanced industrial equipment can be used for production; in the case of large-format printers, robotic arms are used, so it is a technology covering a wide range of product dimensions. Production is relatively accurate even on desktop printers, where it moves on the z-axis within 0.1 mm, in the x and y axes it usually lies in the interval from 0.1 to 0.4 mm [20, 21], while in industrial equipment we move within a tolerance on the z-axis of 0.1 mm and in the x, y axes of 0.2 mm [9]. The technology does not impose increased requirements on the handling of production materials with respect to operator safety [22]. Another advantage of the production technology is a relatively large portfolio of available materials from the field of thermoplastic polymers and elastomers. Their mechanical or thermal properties can be increased by adding metal particles or fine carbon, aramid, or glass fibers. In addition, some manufacturers' devices allow the printing of materials with continuous fibers, which significantly increases the strength of the resulting product [23, 24]. Given the maximum hot end temperature of up to 400 °C, these industrial devices can print "high-performance" polymers, such as Polyetheretherketone (PEEK), Polyetherketoneketone (PEKK) and Polyetherimide (PEI). These materials are characterized by excellent mechanical resistance, especially when printing shells and thin-walled parts, chemical (except sulfuric acid) and temperature resistant parts, up to 250 °C [25].

In the case of manufacturing more complex shapes of products (e.g. overhanging parts), it is necessary to create support structures, which must be removed mechanically. Some materials are hygroscopic and require drying before or during their use. Another disadvantage is the significant mechanical anisotropy [26] in the cross-section of the component, which is caused by the production process of the technology, i.e. that the material is added in layers to previously manufactured and solidified layers. This phenomenon results in reduced adhesion between individual layers and the possibility of defects, especially porosity and delamination (Fig. 3), which are represented by differences in the values of individual parameters, i.e. ductility, tensile strength and bending strength depending on the direction of stress.

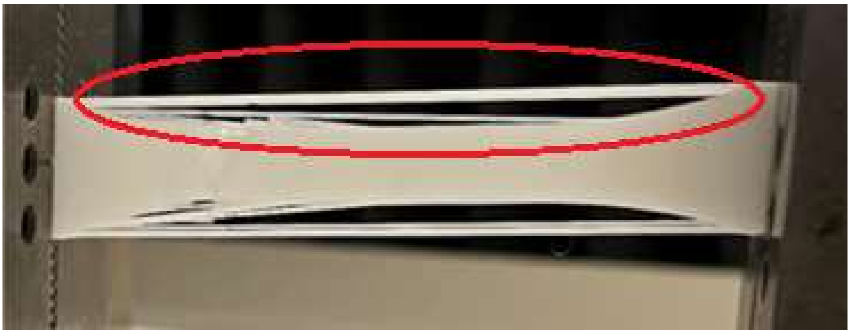

Fig. 3 Delamination of individual layers in a specimen made of polyamide during a tensile test

This disadvantage can be eliminated to some extent by heating the product to the glass transition temperature of the material, but only at the cost of uneven deformation and shrinkage of the product, which is usually unacceptable for functional parts [27]. It is also possible to improve the mechanical properties by adding small or continuous fibers during printing, but only in the *XY* plane. The design of the product and its orientation on the printing surface during production must therefore be adapted to the expected direction of stress on the part. Products do not tolerate combined stress at the load-bearing limits in the horizontal and vertical planes.

2.3 Possible Applications

As already mentioned, the MEX process is widely used in the automotive industry, both in the field of rapid prototyping [18, 19] and in the production of functional parts and fixtures, especially in small-scale production and customization of production lines and vehicles [20].

- As a first example, it is possible to mention the possibility of producing mechanically low-stress parts of vehicle bodies, serving mainly as aerodynamic elements to direct air flow, cases and covers of critical components (Fig. 4a). The most commonly used materials for these purposes are Acrylonitrile Butadiene Styrene (ABS), Polyamide (PA), and Polycarbonate (PC).
- This process can also be used to produce elastic vehicle parts, an example of which is the production of elastic air and liquid tubes and hoses (Fig. 4b); however, due to the impossibility of producing supporting structures and armatures, their use is limited to low-pressure lines of operating fluids or air. They can also be used to produce silent blocks, seals, even for those that must withstand operating fluids. Furthermore, to produce rubber sleeves and protective elements. For these purposes, Thermoplastic Elastomer (TPE), Thermoplastic Polyurethane (TPU), and Styrene Ethylene Butylene Styrene (SEBS) elastomers can be used.

- The technology is also suitable to produce expansion, storage, and balancing tanks for vehicle operating fluids. Fig. 4c shows an example of the use of this technology to produce a coolant expansion tank, which is made of Polypropylene (PP). PA and PC materials are also suitable. The only disadvantage is that the materials, except PC, are not transparent, making it difficult to control the amount of liquid in the tank.

For mechanically and thermally stressed components, high-strength materials that can be produced on industrial equipment from Markforged or Stratasys [21, 22] are suitable. Fig. 4d shows an example of a bearing housing made of PEEK. Other usable materials include PEKK, PEI, and Polyphenylsulfone (PPSF).

Fig. 4 Examples of application of MEX process to produce components for automotive industry: a) vehicle body; b) elastic components; c) expansion and balancing tanks; d) mechanically exposed parts

3 Testing of Specific Properties of MEX Products

For the successful application of the MEX process to a specific application, it is necessary not only to design the component appropriately and select the correct orientation on the printing substrate, but also to choose a suitable material that enables the component to withstand all operational loading conditions. Data sheets are issued for individual materials, where mechanical properties are defined, i.e. ductility in both axes, bending strength, temperature of dimensional stability at atmospheric pressure, tensile strength, and impact toughness. However, in addition to the aforementioned mechanical stress, temperature and other degrading influences affect components of ground military equipment. These influences primarily include exposure to operating fluids. Manufacturers usually issue chemical resistance tables for individual materials [18, 19], but these often define chemical resistance without quantifiable data, using the division of resistance into four groups: excellent, good, fair, and poor. Based on this categorization, it is not possible to effectively decide whether a selected material, for which good or fair chemical resistance is defined, will withstand its exposure for the required period. In addition, the lists contain the influence of a limited list of chemicals from various applications, from organic solvents to hydroxides and inorganic acids. However, operating fluids usually consist of multiple substances; for example, motor oil is a petroleum derivative together with additives containing both organic and inorganic substances.

3.1 Testing of Chemical Resistance

A thorough assessment of the chemical resistance of polymer materials produced by 3D printing to operating fluids is therefore another necessary step for their successful use in the production of replacement parts for ground military equipment. Some research on the chemical resistance of 3D printed products has already been carried out in the past, but this was research in a specific application; as an example, let us mention an experimental verification of the chemical compatibility of manufactured laboratory equipment with chemical solvents, alkalis and acids. In this research, which was carried out at Aalto University in Espoo, Finland [28], changes in the dimensions of the samples were measured, i.e., shrinkage or swelling of the samples. Another team of authors focused mainly on the optical evaluation of the dimensional stability of samples immersed in chemicals, where the cylindrical sample was loaded with a spherical weight and then any disintegration, delamination, or swelling of the sample was monitored [28, 29].

However, for components of ground military equipment, the main thing is to maintain mechanical properties even in the case of long-term or cyclical exposure to operating fluid. Minor changes on the surface of the components or a change in the color of the sample are not essential for the purpose being assessed.

During the exposure of the samples to the degradation environment, serious changes in the surface of the samples were expected, which could result in problems with clamping the sample in the jaws of the tearing machine In addition, the main requirement for the manufactured parts is the need to maintain the dimensions of the product in the full range of operating loads. Therefore, it is not necessary to measure the change in the ductility of the material, since a three-point bending test was used to compare the mechanical properties according to the ISO 178:2019 Plastics. Determination of the flexural properties standard, the shape of the sample and the method of its positioning in the flexural test device can be seen in Fig. 5.

The aim of the first phase of the test was to determine the values of the bending properties of individual materials, which could be compared with data from manufacturers/suppliers.

The essence of the test was to load the test sample at a constant speed with a force with a preload of 2 N. The test specimen with a rectangular cross-section $h \times b$ and dimensions of 4×10 mm was supported by supports at a distance of 64 mm. The test was carried out until the sample broke or a deflection of 5 % was reached. For the extreme deflection limits, the value of automatic test termination at deformation of 20 mm was set. This value was determined due to technical limitations of the test equipment – the main limitation was the length of the loading pin.

The first series of tests were performed with ABS, Polylactic Acid (PLA), Acrylonitrile Styrene Acrylate (ASA), Polyethylene Terephthalate Glycol (PETG), and PA materials. The tested samples were printed on a Bambu Lab X1C printer with a layer height of 0.15 mm and an infill of 100 %. The first series of ten samples were printed and tested for each of the three materials, from which the mean values were calculated. The values were entered into Tab. 2.

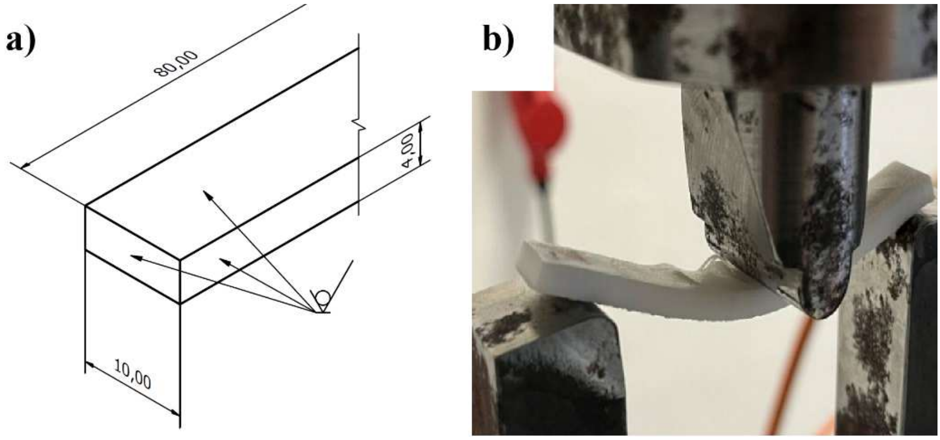

Fig. 5 a) Sample dimensions in mm for three-point bending test according to the standard ISO 178:2019*; b) Testing of the sample in the flexural fixture of the testing machine Zwick Roell* Z100

The second series of samples was immersed in a total of 22 different operating fluids commonly used in military land equipment (Fig. 6), from basic types of fuels and lubricants to brake fluids on both existing bases, i.e. glycol and silicone. The exact list of operating fluids used is shown in Tab. 2. The samples were exposed to fluids for 4 weeks and then subjected to a three-point bending test to determine the value of the bending strength limit and its comparison with the value of the strength limit of the undegraded sample. Some samples showed significant disintegration already when pulled out of the tested liquid, therefore they could not be tested; the values of the bending strength limit for these materials are not given in the table (Tab. 2) and are automatically evaluated as unsatisfactory for contact with the given liquid.

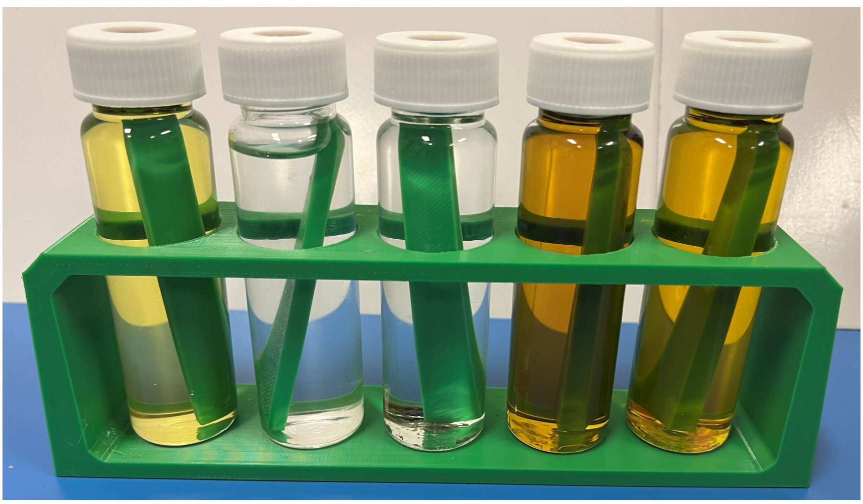

Fig. 6 Example of immersion of PETG samples in operating fluids

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Tab. 2 Average values of maximum bending strength for degradable materials

No.	Operating fluid	Mean value of maximal bending stress for polymeric material [MPa]				
		ABS	ASA	PA	PETG	PLA
0	non-degraded material	61.7	69.1	54.7	67.8	87.2
1	glycol based cooling liquid G11	63.3	68.7	35.5	70.9	93.7
2	ethanol based windscreen washer fluid	60.5	61.7	31.5	70.5	93.0
3	glycol-ether based brake fluid DOT 4	60.8	67.0	48.7	65.3	67.9
4	urea based exhaust fluid AdBlue	63.5	67.0	34.3	69.4	70.3
5	summer washer fluid - surfactants contain	62.3	67.4	29.8	69.3	93.4
6	gear oil SAE 80W-90 API GL-5	57.0	67.9	52.3	72.0	94.1
7	engine oil SAE 5W-30	59.0	67.4	51.3	71.6	93.8
8	distilled water	58.7	68.2	40.2	70.3	91.8
9	saline water – 5 % NaCl	63.4	68.5	42.3	70.1	92.3
10	silicon based brake fluid DOT 5	—	—	49.4	52.2	43.3
11	petrol 95 octane	41.3	57.3	45.0	56.7	68.6
12	diesel fuel	60.7	66.0	50.0	56.9	82.3
13	power steering fluid - VW TL 52146	59.8	62.1	52.6	64.7	86.9
14	automatic transmission fluid ATF Dexron III	60.6	67.2	53.4	66.6	87.4
15	hydraulic oil ISO VG46	61.3	66.7	54.8	72.3	89.6
16	sulfuric acid 30 %	62.1	70.0	41.2	71.5	94.1
17	gear oil SAE 80W-90 API GL-4	61.8	69.7	54.8	68.9	92.6
18	power steering fluid VHLP HYKROL ISO-VG 46	61.4	67.9	49.2	71.2	92.0
19	engine oil SAE 10W40	61.7	66.9	51.1	68.5	91.3
20	kerosene oil	61.1	66.0	51.6	68.0	92.6
21	gear oil SAE 75W/80 GL-5	61.2	66.7	44.8	70.7	90.4
22	plastic grease LV 2-3	62.7	68.7	46.4	69.2	91.2

Fig. 7 shows the output of the bending strength measurement for a selected sample of ABS material, which is degraded by gear oil. The example of comparison of the influence of selected operating fluids can be seen in Fig. 8. The values at individual points were affected by measurement error, therefore, for all measurements, the sixth-degree Ordinary Least Squares polynomial regression was chosen for the purpose of displaying the measured data and subsequent calculations according to the relationship [30]:

$$y = ax^n + a_{n-1}x^{n-1} + \cdots + a_2x^2 + a_1x + a_0 \tag{1}$$

where y – the dependent variable; x – the independent variable; a_i – the polynomial coefficients; n – the degree of the polynomial.

The sufficient accuracy of the regression is demonstrated by the lowest achieved value 0.9996 of the coefficient of determination in accordance with Eq. (2) [31]

$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y}_i)^2} \tag{2}$$

where R – the coefficient of determination; y_i – the measured value; $\hat{y}_i$ – the predicted value; $\bar{y}_i$ – mean of observed values.

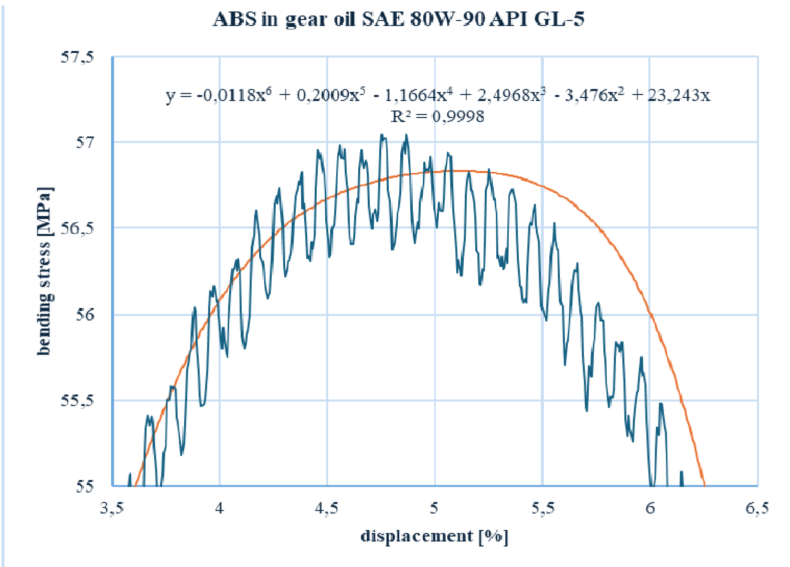

Fig. 7 Course and comparison of measured values of the bending strength limit with the resulting polynomial regression in the area of the strength limit

4 Results and Discussion

4.1 Evaluation of Compatibility of Materials to the Selected Operating Fluid

Fig. 9 and Tab. 2 show a relatively wide range of operating fluids for which the tested materials can be used. The measured values were entered into the table; the percentage limit value of the material usability was set at 90 % of the achieved strength limit for the undegraded material (marked in green). For short-term use within the measured period, i.e. four weeks, in most cases it is realistic to oversize the products by 10 %, so that the geometry of the functional surfaces is maintained.

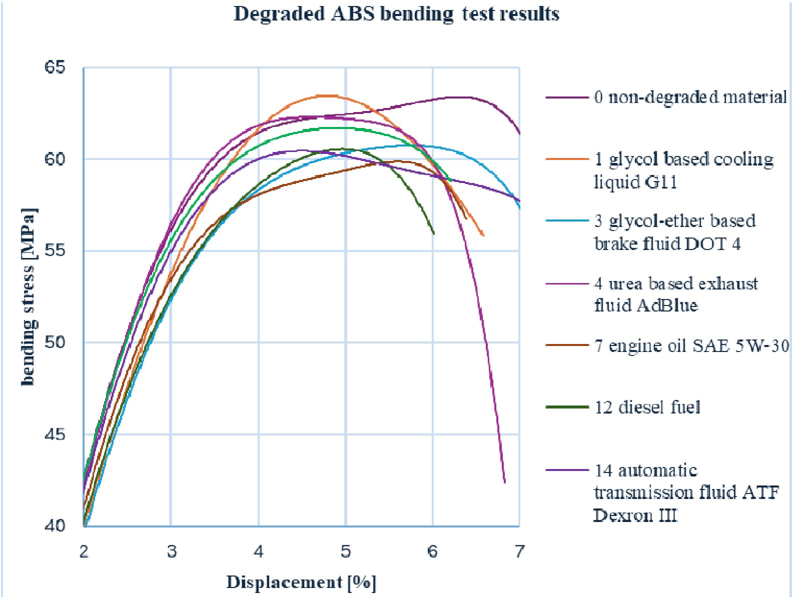

Fig. 8 Comparison of the influence of selected operating fluids on the deflection process and bending strength on a sample made of ABS

The table shows combinations of the degrading operating fluid and the tested material that can be safely used in green. Combinations where the limit value of 10 % decrease was reached are marked in orange, and the use of the material in contact with the specified operating fluid is then to be considered depending on the nature of the stress. Combinations which exclude the use are marked in red.

When evaluating individual materials, it was found that none of the listed materials is suitable for permanent contact with gasoline.

The evaluation (Tab. 2) shows that the most suitable materials to produce temporary replacement parts for ground equipment are ABS and ASA. ABS is not suitable to produce parts that are in contact with DOT 5 brake fluids (silicone-based brake fluids) and gasoline. No significant percentage deviations were measured from the control measurements for other fluids.

ASA material is not suitable for use in the same environments as ABS material. The use of the material in combination with ethanol-based windshield washer fluids is shown to be unsatisfactory. For this fluid, this is a result at the specified limit of applicability. In other cases, no significant changes were found in the bending strength of individual samples were found.

The result of the real use of the above procedure can be seen in Fig. 7. As a representative case, the procedure was applied to the oil filter cover of internal combustion engine of medium tactical truck, where, as a result of tightening above the permitted tightening torque, the metric hexagon of 32 mm is twisted and the cover is destroyed during a subsequent attempt at disassembly, which is related to periodic motor oil change. The 3D model of the component was created using reverse engineering techniques. As part of the redesign of the part, it was necessary to preserve the geometry of the functional surfaces, i.e. the thread for screwing the cover into the filter body, the seat for the O-ring and the upper hexagonal nut 32 mm. On the inner side of the nut, the cavity was removed, which was there to save material during the original injection molding manufacturing process (Fig. 10b – pos. 1.). The thickness of the seat, with which the cover abuts the filter body, was increased by 10 % (Fig. 10b – pos. 2.), a 10 % increase occurred in the wall thickness of the entire component (Fig. 10b – pos. 3.). A comparison of the original part and the replacement produced by additive manufacturing, including the installation of the replacement on the engine of a medium commercial vehicle, can be seen in Fig. 11.

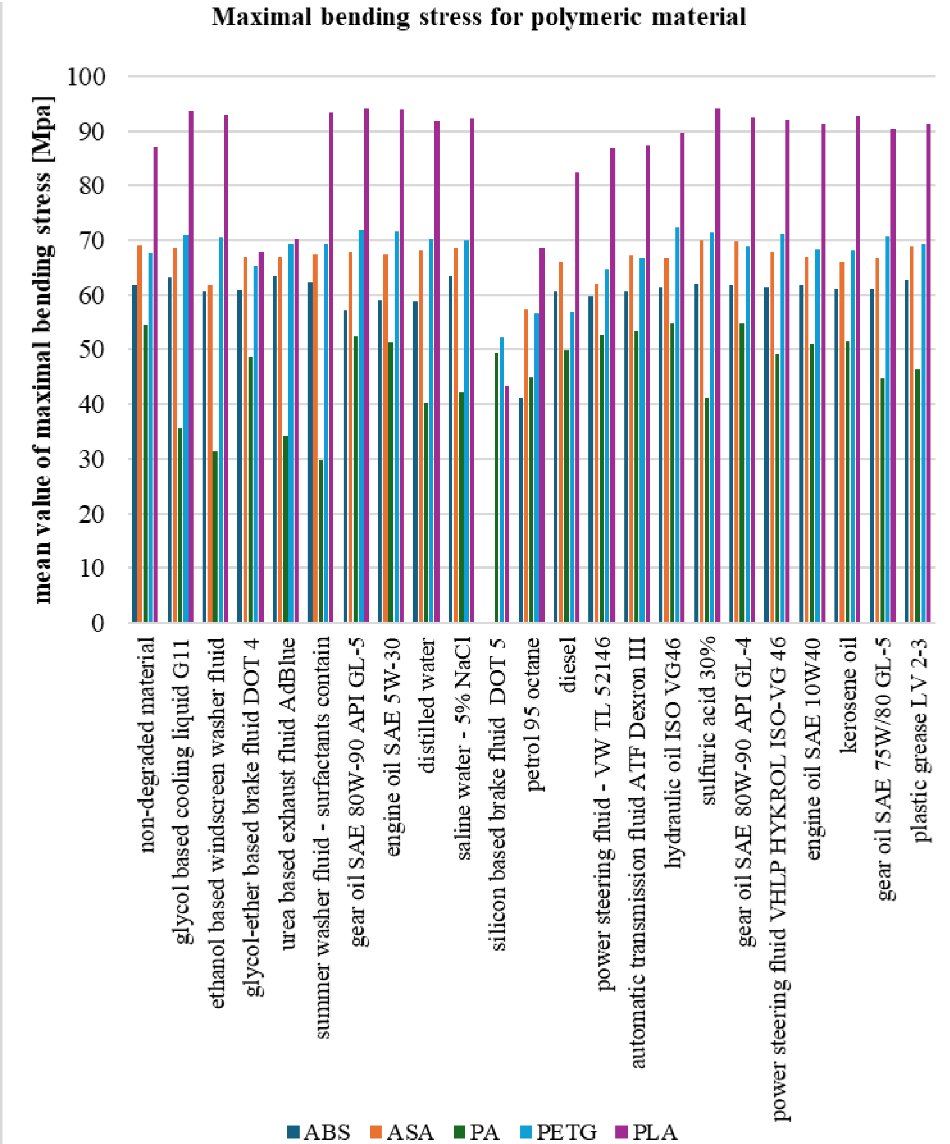

Fig. 9 Comparison of the effect of operating fluids on the bending strength of tested materials

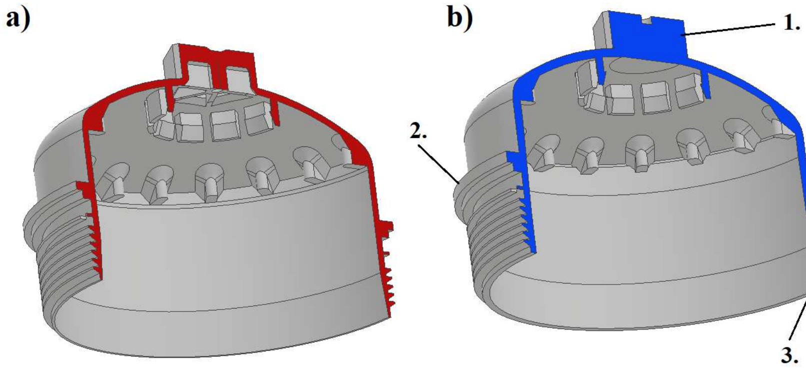

Fig. 10 Cross-section of the oil filter cover: a) original design; b) optimized design: 1. elimination of cavity; 2. increased seat thickness, 3. increased component thickness

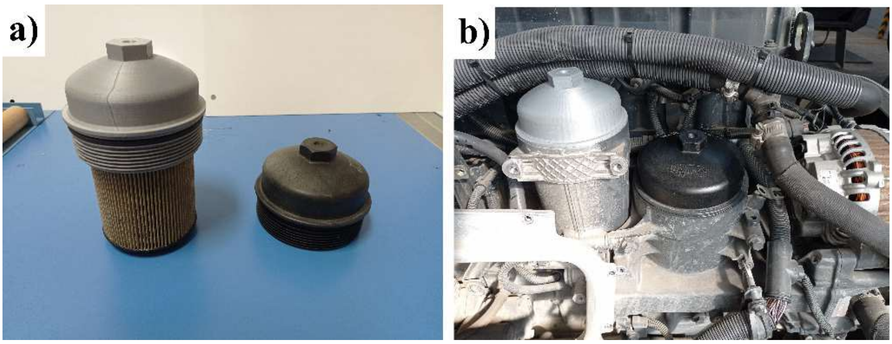

Fig. 11 a) Comparison of the original part and the manufactured replacement part; b) the manufactured replacement part mounted on a medium tactical truck engine

5 Conclusions

As part of the research, additive manufacturing processes that fall into the category of material extrusion of polymer materials were tested. This was mainly done using commonly available production equipment processing a basic set of rather non-technical materials. However, owing to their ease of operation, the simplicity of the production technology – which enables reproducible production quality under varying conditions – and the low complexity of subsequent post-processing, these devices and materials are well suited for use in field conditions, particularly for the manufacture of replacement parts intended for temporary repairs. The research focused primarily on assessing the change in mechanical properties of products under the influence of operating fluids of ground military equipment.

During the research, samples from a set of materials applicable for additive manufacturing in the field, such as PLA, ABS, ASA, PA, and PETG were immersed in a total of 22 commonly used operating fluids and subsequently the change in their mechanical properties, especially flexural strength, was monitored. Based on the experiments performed and their evaluation, usable materials were selected that retained their mechanical properties under the influence of the largest portfolio of operating fluids, while the acceptable limit of the decrease in the flexural strength limit was set at 10 %.

In response to this degradation, a method for redesigning components for additive manufacturing was proposed that accounts for the aforementioned effects and ensures failure-free operation of the equipment for the required period when used as a temporary repair. This procedure was demonstrated on a specific component for which the design and non-design space of component was defined, and the design was optimized with regard to the possible decrease in the mechanical properties of the material under the influence of degradation effects.

To successfully apply this technology for its intended purpose, further research in the field of the effects of degradation effects is necessary. By interweaving with the outputs of the author's previously published research on the effects of thermal cycles and UV radiation on the considered set of materials [32], the selection of usable materials and specific possibilities of use is already being specified. However, when applying pressure, it will be necessary to consider the internal anisotropy of the component in future research, with regard to the specifics of the production technology consisting in the gradual addition of material in layers. The following research should be oriented in this direction.

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