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Prototype of a high dynamic precise axis system based on flexure hinges for the micro positioning of an electrode in the near dry EDM process

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Abstract
For a long time, electrical discharge machining has been an established manufacturing process in mould and tool construction, automotive engineering and medical technology. Due to the dependence from the processing tank and the insufficient dynamic positioning accuracy of industrial robots, the process cannot be performed by a robot until today. In order to regulate the working gap s during the process with a high level of precision and dynamic, this work presents the development and results of a micro axis system based on flexure hinges. Because of their advantages over other mechanisms such as zero friction and backlash, flexure hinges are used in systems where high precision is required. Despite the advantageous properties, research activities have to be done, regarding to the complex and cost-intensive production and the nonlinear behaviour of new materials. Based on these findings the development and production of flexure hinges, made of low-cost plastics with preferred linear material behaviour, was investigated in this work. For the use of various materials, the prototypes were produced by fused deposition modeling. Finally, this paper illustrates the results of the material investigations and shows the advantages, issues and potentials of the materials used. Furthermore, it is shown that the application of low-cost materials and a new concept of flexure hinges resulted in a micro axis system, which performs the dynamic positioning of the electrode in the robot based near dry electrical discharge machining process.

Keywords: Flexure hinges, axis system, micro positioning, near dry EDM

1. Introduction

Since around 1770, when the English chemist and physical scientist Joseph Priestly found the effect of electric spark discharges with the material removal effect [1], and the couple Lazarenko in the year 1943 developed a system to control spark discharges [2], the process has established itself alongside conventional manufacturing processes. Electrical discharge machining (EDM), is a thermal removal process for the production of complex geometries and the finest surface finishes. The removal of material occurs by spark discharges between two electrical conductive materials in a dielectric environment. The EDM machines are equipped with a processing tank filled with an insulating medium, whereby conventional mineral and synthetic oil products based on hydrocarbon compounds are mostly used. A disadvantage of conventional EDM depends on given machine designs related to the limitation in the flexibility of the electrode position. Besides to conventional machining in a full bath with dielectric liquid, approaches with liquid-gas mixtures called near dry EDM (ndEDM), exist [3]. The process variant ndEDM could be realized by other machine structures but further research activities relating to processing technologies are necessary [4]. For the flexible near dry EDM machining, which can be performed by a robot in the future, a highly dynamic and precise positioning systems, which realize the working gap control of the electrode, is required. The results illustrated in this scientific paper show the development and analyse of flexure hinges, made of low-cost plastics, which were manufactured by fused deposition modeling (FDM). In addition, a new concept of a micro axis system based on flexure hinges, for the dynamic precision positioning of the electrode for the robot based ndEDM process, will be presented.

1.1 Near dry EDM

Since the 1980s, the method of ndEDM exists, where a liquid-gas mixture consisting of deionized water and air is fed to the process site. Many research activities e.g. Tanimura et al. [3] Kao et al. [5] and others [6, 7], show the process-related advantages like a stable process, a higher material removal rate (MRR) with larger gap distances and lower discharge energy input compared to conventional EDM. Due the oxidation effect particles were isolated, which increased the process stability. Moreover, the high mol mass M_O = 31.99 g/mol and density ϱ_O = 1,184 kg/m^3 of oxygen lead to high pressure effects in a high flow velocity in the working gap *s*, which prevents short-circuits [8]. Furthermore, the higher thermal conductivity κ and specific heat capacity c_p of water has a positive influence on the erosion process. In addition, the evaporation of the water leads to a strong cooling of the tool ad workpiece electrodes, which reduce the electrode wear [3, 6].

1.2 Flexure hinges

Flexure hinges realize the joint movement from defined elastic deformation. As a result of the geometric design, the deformations preferably take place in the desired direction of movement. This structure results in advantageous properties such as zero friction and backlash as well as wear and maintenance freedom [9]. Due to their advantages, flexure hinges have long been successfully used in nano and micro positioning technology, semiconductor tools or microelectromechanical systems. For their high permissible fatigue limit, flexure hinges are currently manufactured from cost-intensive materials, such as a crystalline CuAlNiFe and shape memory alloys nickel-titanium, silicon or novel plastics e.g. PEEK and polyamide [10, 11]. Depending on the material, the high precision fabrication of flexure hinges is expensive, which means that the area of application is currently very limited. Armendariz et al. [12], manufactured first flexure hinges by FDM and achieved the highest results in the final strength of an axial static force in terms of load capacity for PLA, PETG and nylon and showed the potential for the additive manufactured flexible structures.

1.3 Polymers and additive manufacturing

Polymers consist essentially of organic substances build-up of low molecular weight building blocks (monomers). Due to their mechanical behaviour, they are classified according to the molecular structure and the consequent behaviour into: thermoplastics, thermoplastic elastomers, elastomers and thermosets. Because of their specific properties and their editing, processing and application opportunities, polymers have become a high and increasing importance [13]. Thermoplastics considered in this scientific work are uncross linked plastics which have an energy-elastic (steel-elastic) behaviour at operating temperatures and above them, they become soften and melt. The reason for the choice of these polymers for the production of flexure hinges in this study, are further advantages like a high fatigue strength S_{Nf}, flexural strength σ_{fM} and the recyclability [14]. Fused deposition modeling (FDM), or fuse filament modeling (FFM), is one of the most common additive manufacturing (AM) technique and offers the opportunity to produce complex three dimensional geometries very cost-effectively. The mechanical properties of additive fabricated components are determined by the process parameters (filament and nozzle diameter, nozzle temperature, cooling rate) and design parameters such as build orientation, grid angle, layer height and fill percentage. In recent years, several studies have been carried out to investigate at the effects of design parameters on flexural strength σ_{fM} and flexural modulus E_f of FFM 3D parts [15]. According to Ravindrababu et al. [16], taking the grid angle of zero degree along the loading direction obtain the highest flexural strength σ_{fM} and flexural modulus E_f compared to 90° degrees transverse orientation. Additionally, an increase in the layer height leads to a reduction of the mechanical properties σ_{fM} and E_f [17, 18]. It can be concluded that samples printed in the xyz direction obtain a high tensile strength σ_{TS} and flexural modulus E_f, followed by xyz compared to zxy [19, 20].

2. Methodology

The aim of this scientific work was the development and construction of a micro axis system based on additive manufactured flexure hinges made of polymers. This should provide a high dynamic gap control (f_{ero} = 100 Hz) for the electrode in robot-based near dry EDM proceedings with an amplitude of $0.1 \le x_a \le 100$ µm and a positioning accuracy of $P_a \le 3$ µm. Initially, a concept for a flexure hinge model based on Ivanov [21] was designed and optimized by a FEM analysis with software *Solidworks*, to optimizes the geometry with regard to stress reduction in the stressed cross section. In order to decrease the production costs, the flexure hinges were made of various polymers by using FDM with the Ultimaker 3, Ultimaker BV Netherlands. The selected polymers like polylactides (PLA), acrylonitrile butadiene styrene (ABS) and a tribological optimized polyethylene terephthalate compound (triboPET), were chosen on the basis of a high flexural modulus E_f, flexural strength σ_{fM} and bending stiffness S_F, see table 1. Based on the scientific studies the printing direction of 0° degree, longitudinal printing with the orientation xyz and minimum layer height h_l = 0.02 mm well as 100 % filling were chosen. The subsequent investigations on the fatigue testing machine should provide information about the fatigue behaviour and values for determining the statistic fatigue limit [22]. To analyse the surface before and after the test, the digital microscope model VHX-2000 by Keyence was chosen. In addition, an analysis to identify the pores distribution, gaps and defects was carry out by the digital microscope DM1750 M, Leica Microsystems GmbH Germany. Based on the results, a concept for a 1-DoF axis system based on flexure hinges was developed.

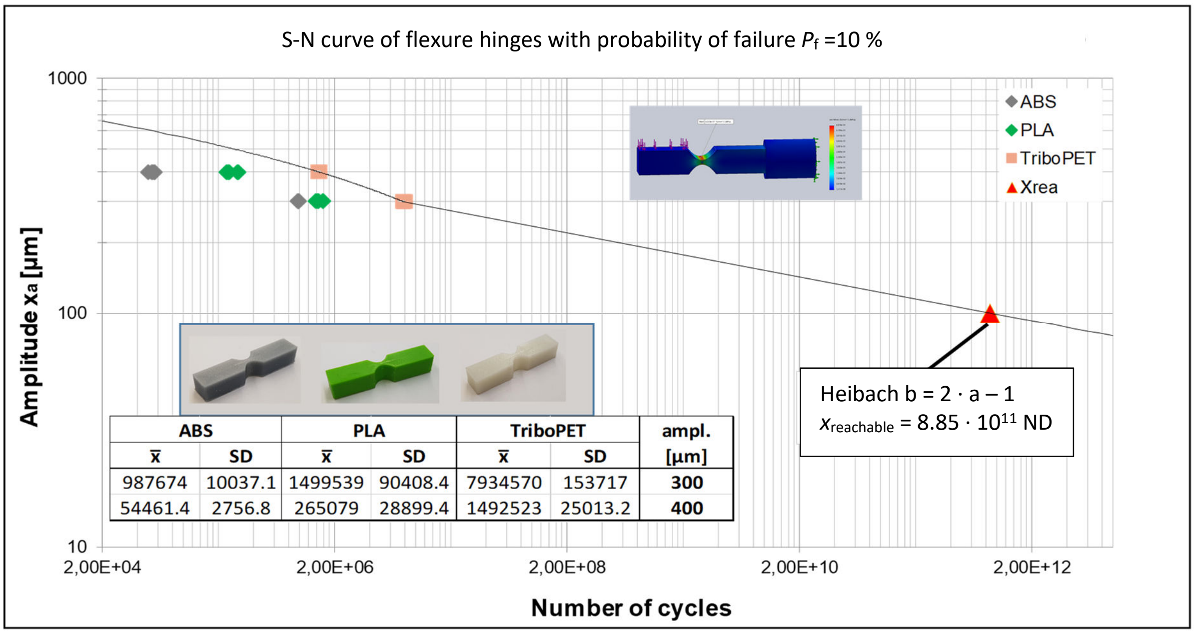
Table 1 Mechanical properties of polymers for FFM of the flexure hinges [23-25].

	Unit	PLA	ABS	triboPET
Structure	-	amor-phous and crystalline	amor-phous	semi-crystalline
Flexural strength σ_{fM}	MPa	103	70,5	79,99
Flexural modulus E_f	MPa	3150	2070	2251
Yield strength σ_D	N/mm²	49,5	39,0	53,20
Bending stiffness S_f	N·mm²	4429	2910	3165

3. Results

3.1. Dynamic fatigue testing and probability of failure

After preliminary tests with different amplitudes (displacements), five samples with displacements of x_1 = 300 µm and x_2 = 400 µm at a frequency of f_t = 25 Hz were tested on the fatigue testing machine Eltron E 1000, by Instron GmbH Germany. The material triboPET achieved the highest number of load cycles $x_{triboPET}$ = 7 934 570 ND (x_1 = 300 µm) and $x_{triboPET}$ = 1 492 523 ND (x_2 = 400 µm) with a standard deviation of s_{x1} = 153 717 ND and s_{x2} = 25 013 ND. With the results from the fatigue test, the stochastic connectivity could be mathematically proven and the statistic distribution parameters *θ*, *T* and *b* for determining the probability of failure $P_f(x_{10})$ in the tension/compression alternating range could be determined. The S-N curve (Wöhler) and the static estimation of the fatigue limit according to Heibach with $b = x \cdot 2 + a$ was calculated. The double logarithmic representation, see Fig. 1, shows the results of the fatigue test and the estimated fatigue limit $x_{err} = 8.85 \cdot 10^{11}$ ND of a TriboPET specimen with a probability of failure P_f = 2 %.



ABS		PLA		TriboPET		ampl.
x̄	SD	x̄	SD	x̄	SD	[µm]
987674	10037.1	1499539	90408.4	7934570	153717	300
54461.4	2756.8	265079	28899.4	1492523	25013.2	400

Figure 1. Wöhler curve (S-N curve) of flexure hinges with cycles at different amplitudes (x_1 = 300 µm, x_2 = 400 µm) and a frequency of f_t = 25 Hz; According to Heibach the fatigue limit: $x_{reachable} = 8.85 \cdot 10^{11}$ limit cycle number for infinite life (ND) of triboPET with an amplitude x_a = 100 µm.

3.2. Analyse of sample

The results of pores analysis with a magnification of 1000x (Fig. 1 a, b and c), showed only a few pores with a proportion of 2 % and a pore size between 1 µm ≤ d_p ≤ 2 µm, what Guessasma et al. confirmed in their studies [26]. Fig. 1 (d) shows the microsection of the cross section of a printed sample before loading. A pattern of small triangles, which are equally symmetrically distributed could be observed. The small gaps recognised as triangles occurs by the printing strategy and the choice of design parameters, what the results of Yang et al. confirmed [27]. Furthermore, as shown in Fig. 1 e) and f), two cases of defects could be observed under excessive stress load. First, an initial shear stress dominated debonding occurs between the adjacent filaments, which take place where material is missing, see Fig. 1 e). Second, a normal stress controlled straight cracking of the filaments itself occurs, see Fig. f). Both cases lead to the failure of the samples, according to Garg et al. [18]. For the application in an axis system, the application range will therefore be far below the test amplitudes in order to be able to achieve a high number of load cycles.

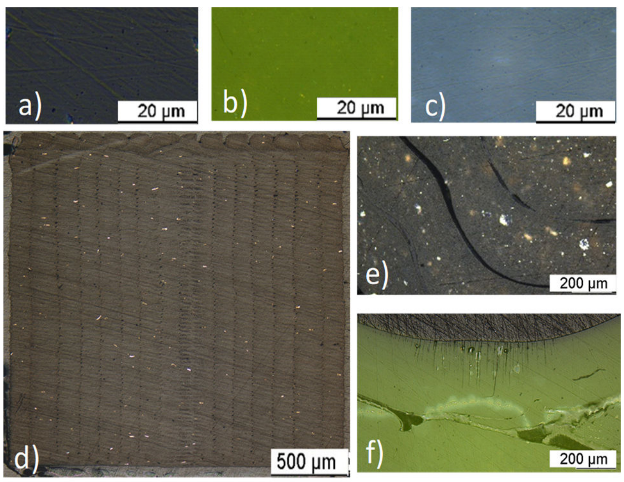


Figure 2. Pores analysis a) ABS, b) PLA and c) tribePET; (d) microsection of triboPET; (e) debonding between filaments of PET; f) cracks due to high load of PLA.

4. Axis system based on flexure hinges

On the basis of the findings from the fatigue test and the sample analysis, a 3D model for an axis system was developed, which realizes an displacement amplification of 1:5 with an amplitude of 0.1 ≤ x_a ≤ 100 µm. After this, mounting bracket were added to fix the system at the housing (Fig. 3). This additionally increases the total bending stiffness S_f and rebound behaviour of the system, which enable amplitudes at higher frequencies. After this, a 3D model was manufactured (AM) with the material triboPET and subsequently examined in terms of amplitude measurement. It was found out that the results (FEM) of the theoretical amplitude deviates by 5 % from the measured values of the real model. The study shows that the results of a FEM analysis, in relation to the displacements of flexure hinges systems, are suitable as a prediction.

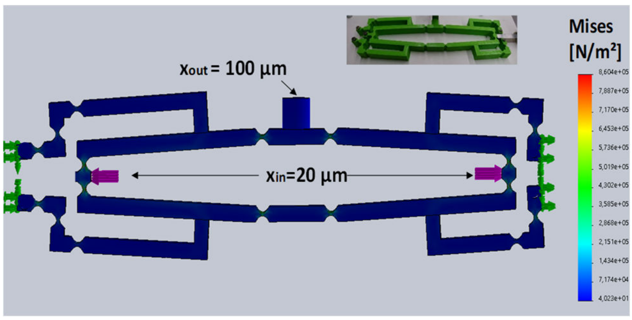


Figure 3. Prototype 3D model micro axis system based on flexure hinges with an amplitude amplification 1:5 and a maximum Mises Stess of $s_{max}=8.6 \cdot 10^5$ N/m².

After the investigations, a prototype with a clamping and adjustment for a multi-layer piezo actuator was designed, as well as a jig for an electrode holder and a system housing, see Fig. 4. Due to a slight push on the electrode, the piezo clamping opens and the acuator can be mounted. By means of an device, the actuator can be further adjusted. The system provides a high dynamic gap control (f_{ero} = 100 Hz) for the electrode in robot based near dry EDM proceedings with an amplitude of 0.1 ≤ x_a ≤ 100 µm and a positioning accuracy of P_a ≤ 3 µm.

The amplitude of the electrode can measured by a piezo sensor or a strain gauge. For the application of the robot based ndEDM, the working gap s can be detected by the gap voltage u_e.

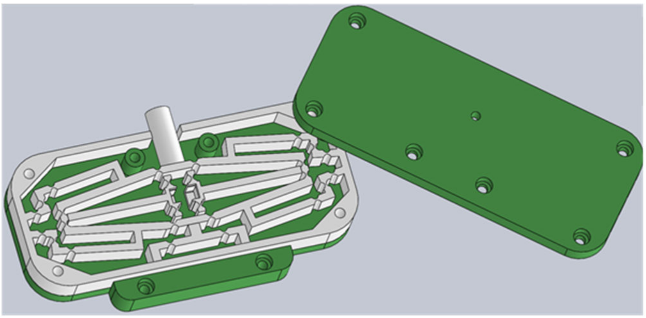


Figure 4. Prototype of flexure hinges based axis system with clamping for a multi-layer piezo actuator and a jig for the electrode. Outer dimensions: 95 · 190 · 36 mm, made of triboPET.

5. Summary

This scientific work shows the methodological development of a micro axis system based on flexure hinges, which was fabricated by additive manufacturing by means of FDM. Based on existing methodologies, a flexure hinge was geometrically designed, regarded to stress reduction in the stressed cross section, and optimized by means of a FEM analysis. The subsequent investigation on the fatigue testing machine with two amplitudes of $x_1 = 300$ µm and $x_2 = 400$ µm enabled a statistic estimation of fatigue limits with a probability of failure $P_f = 10$ % according to Wöhler (S-N curve) and Haibach. The results showed that the material triboPET and PLA had the highest number of load cycles, whereby triboPET reached $x_{triboPET} = 7\,934\,570$ ND ($x_1 = 300$ µm) and $x_{triboPET} = 1\,492\,523$ ND ($x_2 = 400$ µm). Furthermore, the analysis of the samples showed that two cases of defects, an initial shear stress dominated debonding between the adjacent filaments and a normal stress controlled straight cracking of the filaments itself, occur due to high loads. On the basis of the findings a micro axis system was developed, which realized an displacement amplification of 1:5 from the piezo actuator $x_a = 20$ µm to $0.1 \leq x_a \leq 100$ µm. To reach displacements at high frequencies ($f_{ero} = 100$ Hz), the model was stiffened so that the total bending stiffness S_f and rebound behaviour of the system increased. The results of this research presented in this paper show that an axis system based on flexure hinges can be fabricate by additive manufacturing, which offers new opportunities for the production and the area of applications. In Addition, the prototype of a novel axis system obtains the high dynamic precise positioning of the electrode for the robot based near dry electrical discharge machining.

References

[1] Webzell S The first steps in to EDM in Machinery **159** Findlay Publ. Ltd Kent p 41 2001

[2] Lazarenko B R and N J, Electrical Erosion of Metals in Russian Gosenergoisdat Leningrad 1944

[3] Tanimura T, Isuzugawa K, Fujita I, Iwamoto A and Kamitani T 1989 Development of EDM in the Mist *Proceedings of Ninth Int. Symposium of Electro Machining (ISEM IX)* Nagoya **9** pp 313–16

[4] Krishnakant D, Kuldeep C, Akshay D, Omkar B An environment-friendly and sustainable machining method: near-dry EDM *Materials and Manufacturing Processes* 2019 pp 1307-15

[5] Kao C C, Tao J and Shih A J Near Dry Electrical Discharge Machining *Int. J. Mach. Tools Manuf*. 2007 **47** pp 2273–81

[6] Fujiki M, Ni J and Shih A J Investigation of the Effects of Electrode Orientation and Fluid Flow Rate in Near-Dry EDM Milling *Int. J. Mach. Tools Manuf.* 2009 **49** pp 749–58

[7] Gholipoor A, Baseri H and Shabgard M R Investigation of near dry EDM compared with wet and dry EDM processes *J. of Mechanical Science and Technology* 2015 **29** pp 2213–18

[8] Schimmelpfennig T-M *Trockenfunkenerosives Feinbohren von Hochleistungswerkstoffen* Berichte aus dem Produktions-technischen Zentrum Berlin 2016 Dissertation(Uhlmann E: Stuttgart) Fraunhofer IRB

[9] Hopkins J B Designing hybrid flexure systems and elements using Freedom and Constraint Topologies 2013 *Mech. Sci* **4** pp 319–31

[10] Linß S, Henning S and Zentner L Modeling and Design of Flexure Hinge-Based Compliant Mechanisms. Intech Open Technische Universität Ilmenau *Kinematics, Kinematics - Analysis and Applications* 2019

[11] Teo T J, Yang G and Chen I-M Compliant Manipulators *Handbook of Manufacturing Engineering and Technology* Springer-Verlag London 2014 *Compliant Manipulators* 102 pp 2229–2300

[12] Armendariz C O B, MacDonald E, Roberson D A, Ruiz-Huerta L, Maldonado-Macias A, Valadez-Gutierrez E, Caballero-Ruiz A and Espalin D Folding behavior of thermoplastic hinges fabricated with polymer extrusion additive manufacturing Springer-Verlag London Ltd 2019 *The int. J. of Advanced Manufacturing Technology* **105** pp 233–245

[13] Ito S and Aoki H Nano-Imaging of Polymers by Optical Microscopy *Polymer Analysis Polymer Theory. Advances in Polymer Science* 2005 Springer Berlin **182** pp 131-169

[14] Weißbach W, Dahms M and Jaroschek C. Kunststoffe (Polymere) *Werkstoffe und ihre Anwendungen* 2018 Springer Vieweg Wiesbaden **20** pp 367-97

[15] Anoop M S and Senthil P Homogenisation of elastic properties in FDM components using microscale RVE numerical analysis *J of the Brazilian Society of Mech Sc. and Eng.* **12** 2019 p 540

[16] Ravindrababu S et al. Evaluation of the influence of build and print orientations of unmanned aerial vehicle parts fabricated using fused deposition modeling process *J. Manuf. Process* **34** 2018 pp 659–666

[17] Alafaghani A and Qattawi A Investigating the effect of fused deposition modeling processing parameters using Taguchi design of experiment method *J. Manuf. Process* **36** 2018 pp 164–74.

[18] Garg A, Bhattacharya A and Batish A Chemical vapor treatment of ABS parts built by FDM Analysis of surface finish and mechanical strength *Int. J Adv. Manuf. Tech.* 2017 **89** pp 2175–91

[19] Zelený P et al. The mechanical characteristics of 3D printed parts according to the build orientation *Appl. Mech. Mater* **474** 2014 pp 381–386

[20] Dawoud M et al Mechanical behaviour of ABS: an experimental study using FDM and injection moulding techniques *J. Manuf. Process* **21** 2016 pp 39–45.

[21] Ivanov I Methodical Development of a Parallel Kinematic Positioning System Based on Monolithic Structures with Flexure Hinges Dissertation 2016 RWTH Aachen University Verlag Mainz

[22] Schlottmann D and Schnegas H Auslegung von Konstruktions-elementen Sicherheit, Lebensdauer und Zuverlässigkeit im Maschinenbau Springer-Verlag GmbH Berlin VDI-Buch **3** pp 123-44

[23] ABS Datasheet, Ultimaker https://ultimaker.com/download/74640/ UM180821%20TDS%20ABS%20RB%20V11.pdf 10.2019

[24] PLA Datasheet, Ultimaker https://ultimaker.com/download/67934/TDS%20PLA%20v3.011.pdf 10.2019

[25] TriboPET Datasheet Institut für Polymertechnologien e.V., www.ipt-wismar.de 09.2019

[26] Guessasma S, Belhabib S and Nouri H Significance of pore percolation to drive anisotropic effects of 3D printed polymers revealed with X-ray µ-tomography and finite element computation *Polymer* **81** 2015 pp 29-36

[27] Yang L, Li S, Li Y, Yang M and Yuan Q Experimental Investigations for Optimizing the Extrusion Parameters on FDM PLA Printed Parts ASM *Int. J. of Mat. Eng. and Perf.* 2019 **28** pp 169–82