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Original Research Article

Additive manufactured versus traditional osteosynthesis plates - a finite element analysis

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Additive Manufacturing (AM) is rapidly gaining acceptance in healthcare. Its use enables the design and production of more complex geometries than traditional subtractive manufacturing does with specific materials such as polyetheretherketone (PEEK). For orthopaedic applications highly optimized structures, e. g. bio-mimicking implants or light-weight hollow implant bodies, can be produced. In this paper a direct comparison between PEEK and titanium osteosynthesis plates is achieved with a finite element analysis. By that, pros and cons of PEEK as implant material are discussed and different use cases identified. For the comparison a generic osteosynthesis plate for diaphysis is designed. The exceeding of the yield strength even at low bending and torsional loads highlights the problems that occur when applying PEEK implants at locations which are affected by moderate mechanical loads. Since fracture stabilisation is the main function of osteosynthesis plates, stiffness is a highly relevant property of these. Therefore, a direct exchange of titanium to PEEK would increase the risk of non-union. In conclusion, a different structure or an improved material, e. g. carbon fibre PEEK composite, is required for loaded locations to replace metallic implants.

I. Introduction

Polyetheretherketone (PEEK) [1–3] and titanium [4, 5] are both materials used for osteosynthesis. PEEK as a relatively new material is known for several helpful properties such as strength and elastic modulus similar to bone. This shall prevent stress shield effects, meaning the degradation of bone due to less loading of the bone according to Wolff`s Law. PEEK also doesn`t lead to artefacts in CT or x-ray scanning but is transparent for x-rays and MRI compatible. It has biocompatible and chemically inert properties. Furthermore, PEEK can be produced by additive manufacturing [1]. This is becoming increasingly important in clinical settings such as orthopaedics and trauma surgery [1, 6].

On contrary, metallic implants, for example, made of stainless steel, titanium, titanium alloy, gold or cobalt chromium alloy, have been deployed for a long time and appreciated for their good mechanical behaviour. The strong mechanical properties, high strength and elastic modulus, can lead to loosening effects at the interfaces between bone and implant. Titanium is a good-known and established material for bone implants as osteosynthesis plates [1, 7]. Furthermore, titanium has an excellent biocompatibility. In comparison to stainless steel which also is often used for osteosynthesis plates titanium leads to less artefacts in CT scans. Moreover, a titanium plate has a 40 % reduced mass compared to a stainless steel plate of the same geometry because of its lower specific density [8].

This work aims to investigate the different behaviour of generic osteosynthesis plates of the two presented materials, titanium and PEEK, under different, typical load cases with a finite element method (FEM).

By that, an evaluation of the main function of osteosynthesis plates, the stabilisation of a fracture, should be performed with regard to size and stress yielding effect

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and suggestions for additively manufactured PEEK osteosynthesis plates shall be derived.

Stabilisation of the fracture is the main function since small movement can lead to improved healing but higher grade movement leads to delayed or failed healing processes [9, 10]. Many other factors, including age, sufficient blood perfusion, malnutrition, influence the bone healing as described in [10]. Some of these factors relate to the choice of implant, e. g. sufficient blood perfusion [10].

II. Material and methods

The used FEM tool is *ANSYS Multiphysics 2020 R1* (ANSYS, Inc., Southpointe, USA). The mechanical module was chosen and as reference geometry a self-developed generic plate was integrated as a CAD model. A technical drawing of the plate is shown in fig. 1. The used materials for the simulations are PEEK and titanium grade 2. Material data is described in table 1. The three main types of loading that an osteosynthesis implant must withstand are described in the literature as torsion, axial compression, and bending [11]. Therefore, the four investigated load cases were axial compression, bending, torsion and a combination of all three loads.

Due to preliminary investigations on the mechanical behavior with higher loads, which are reported in literature [12], all forces and moments were set to a smaller values to assure that the results are in a linear region. A linear elastic loading scenarios is favorable since a plastic deformation which permanently changes the position of the fractured, operatively aligned bone parts is failing the main function of the osteosynthesis – the stabilization. As axial and bending force a load of 50 N were chosen. 5 Nm was set as the torsional moment. The combination consisted of 16.6 N axial and bending force as well as 1.66 Nm torsion moment. Fig. 2 illustrates an overview of the load cases.

To evade errors due to the transmission of loads, e. g. at the threads and between screw and bone, the forces were applied directly on the osteosynthesis plate. The setup of the FEM study, to investigate only the osteosynthesis plate instead of the compound structure with bone and screws, leads to a limitation of the study since the effects of load transfer and thread are neglected. This simplification enables the investigation of the worst-case scenario for the osteosynthesis plate in each load case by applying the load in the outer screw threads.

To investigate the worst-case scenario of each loading case, the fixed support as well as the load were applied at the opposing other outer screw threads. So, as boundary condition the fixed support and the force are on the opposite sides at the outer screw threads.

The mesh was refined until the relative change of the resulting stress and deformation was below 10 % in comparison to the previous iteration step. This led to 21205 elements (PEEK) and 21205 elements (titanium) for the bending load case, to 139578 elements (PEEK) and 137755 elements (titanium) for the torsional load case, to 34270 elements (PEEK) and 34625 elements (titanium) for the axial load case, and to 146980 elements (PEEK) and 135705 elements (titanium) for the combined load case.

Table 1: Material data at 37° C (simulation temperature)

Mechanical properties	**PEEK**	**Titanium Grade 2**
Young`s modulus	3.78 GPa	102 GPa
Shear modulus	1.35 GPa	37.5 GPa
Bulk modulus	6.3 GPa	121 GPa
Poisson's ratio	0.4	0.36
Yield strength	90.9 MPa	315 MPa

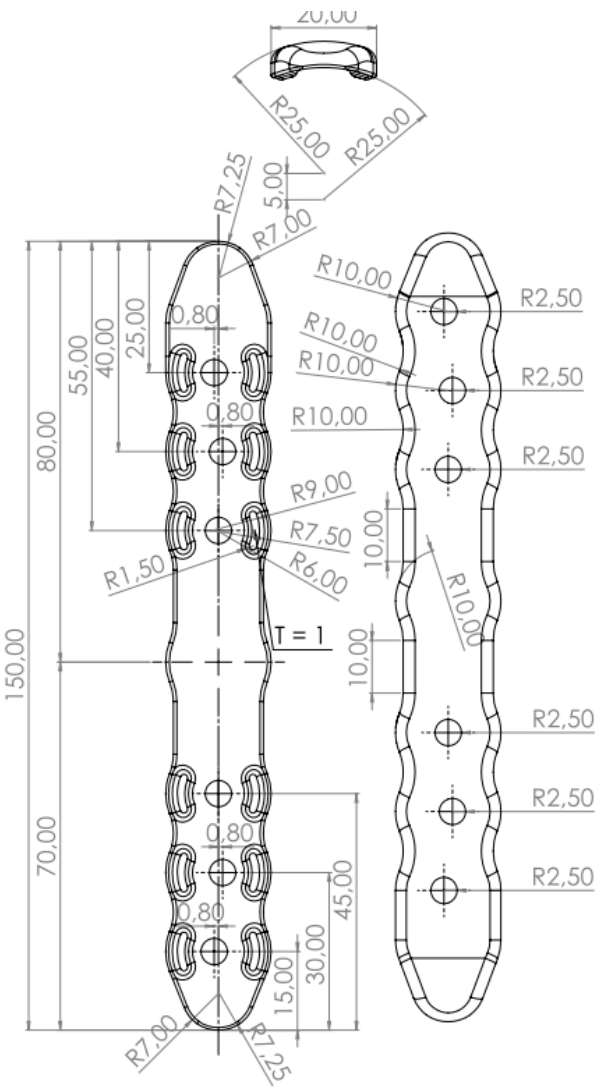

Figure 1: Technical Drawing of the generic osteosynthesis plate with supporting lugs on the bone-facing side to protect the periosteum and mechanical reinforcement around the drilled screw threads as well as the centred shaft area.

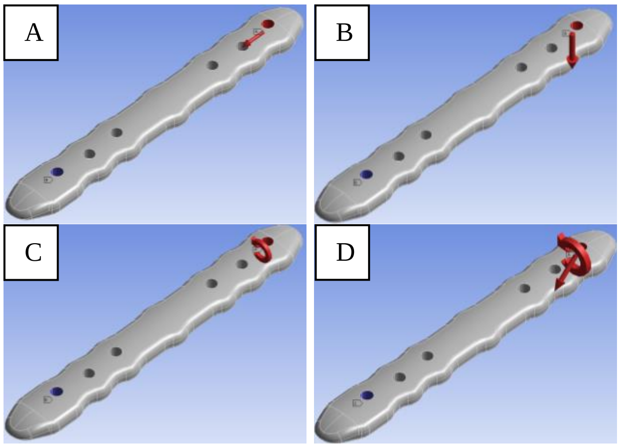

Figure 2: Load cases of the osteosynthesis plates with forces and moments (applied at the red screw thread) as well as fixed support (applied at the blue screw thread). A: Axial loading (50 N), B: Bending (50 N), C: Torsion (5 Nm), D: Combined loading (Axial and bending: 16,6 N, Torsion 1,66 Nm).

III. Results and discussion

Table 2 shows the resulting maximal stresses and deformations as well as the averaged values over the whole osteosynthesis plate.

Table 2: Simulation results

Load case	Stress, maximum [MPa]	Stress, average [MPa]	Deformation, maximum [mm]	Deformation, average[mm]
Bending PEEK	132.14	28.35	32.89	5.55
Bending Titanium	138.4	29.42	1.28	0.22
Torsion PEEK	126.23	35.34	7.74	2.18
Torsion Titanium	125.15	34.92	0.28	$6.76 \cdot 10^{-2}$
Axial Load PEEK	3.08	0.48	0.43	0.13
Axial Load Titanium	2.642	0.48	$1.1 \cdot 10^{-2}$	$3.38 \cdot 10^{-3}$
Combined Load PEEK	72.163	14.06	13.74	4.08
Combined Load Titanium	68.961	13.56	0.46	0.14

In fig. 3 the stress distribution over the osteosynthesis plate is shown for the four load cases. As it can be seen in the results of table 2, the stresses of the same loading cases don`t differentiate distinctly. Since stress is dependent on the force and the geometry – which is the same for both cases – this indicates that the simulation results are valid. Small deviations in the calculated stresses between PEEK and titanium plate can be explained by calculation errors, for example, due to significant differences in the deformation of the plates, which slightly affects the geometry or differences in the meshes. Therefore, in fig. 3 and 4 the material type is neglectable. More interesting is the comparison of the yield strength of the material with the maximum stress. The yield strength of PEEK is only 90,9 MPa which is lower than the stresses at the plate. This would lead to permanent plastic deformation instead of reversible elastic deformation. Thus, for repeatedly loading of the PEEK osteosynthesis plate with load case bending and load case torsion the PEEK osteosynthesis plate would have a permanent damage leading to a deprivation of the main function, the stabilisation of the fracture.

A limitation is that in this simulation only the worst-case scenario is investigated by applying the full load and the fixed support on the contrary outermost screw threads. In a realistic situation this load would be distributed over the screw threads of the one side of the fracture gaps as well as the support. This is dependent on the used screw threads which lead to a high number of different scenarios with unclear distribution of load and fixed support. Since the application of screws can differ and their influence shouldn`t be part of this investigation, the worst-case scenario is used. Thus, the calculated stresses and strains are lower if the loads and fixed supports are more distributed over the screw threads on both sides of the fracture gap.

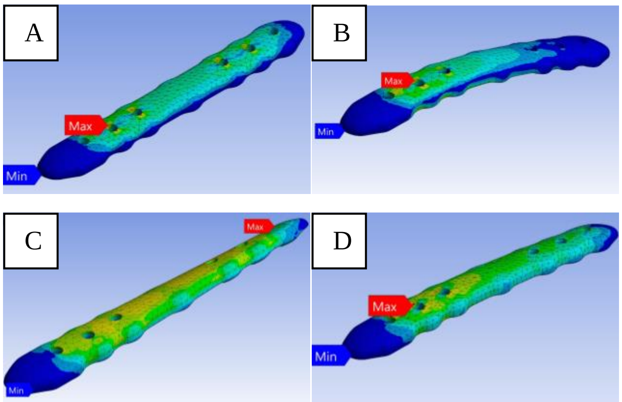

Figure 3: Overview of the stress distribution. A: Axial loading (50 N), B: Bending (50 N), C: Torsion (5 Nm), D: Combined loading (Axial and bending: 16,6 N, Torsion 1,66 Nm). Maximum stresses differ.

The load cases bending, axial and combined load have the stress maximum at the same spot – the second screw hole after the fixation of the plate. An exception is the torsional load case where the maximum is at the screw hole at which the moment is applied.

This shows that an investigation of the occurring types of loads is essential to understand the geometric areas of a plate which have to be supported. In this case, the examined generic osteosynthesis plate already has an increased width at each hole to account for the large stress values in these regions.

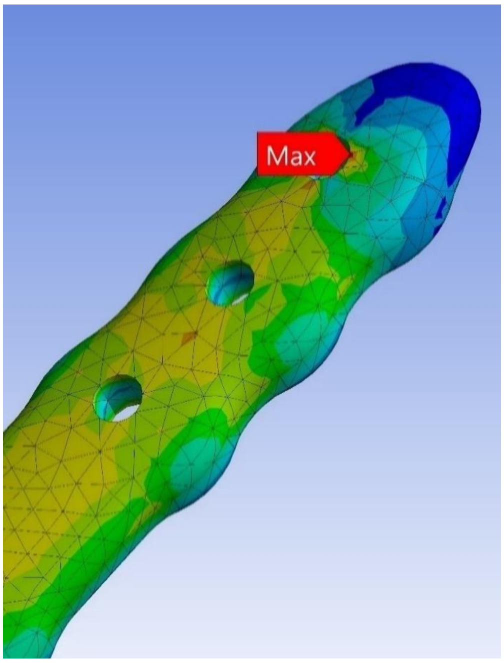

Figure 4: Torsional loading - point of maximum stress

Fig. 5 illustrates a linear amplified deformation (factor 30) in load case bending for the PEEK and the titanium osteosynthesis plate. The deformation due to bending is dependent on the bending stiffness. The bending stiffness results from the second moment of area multiplied by the Young's modulus. Since the second moment of area is geometry dependent, the only difference is based on the Young`s modulus. Since the factor between the two Young`s moduli is around 27, the bending deformation of the PEEK osteosynthesis plate is expected to differ equally to this factor in comparison to the deformation of the titanium osteosynthesis plate. This is indeed the case.

To compensate for this, an increase of the dimensions is required. For a simplified rectangular shape, the deformation is proportional to the power of three of the height and only depends linearly on the width of the plate. Therefore, the height/thickness would have to be tripled, the width to be increased twenty sevenfold or a combination of these would be required to limit the deformation of the PEEK plate to that of the titanium plate. Another option to increase the stiffness against bending is to change the shape to a more tube-like structure. Each of these solutions would lead to an increase of the dimension which, for example, would interfere with the vasculari-zation during healing, increase the wounds during operation and displace tissue. In locations like the tibia shaft a higher thickness can lead to complications during closing of the wounds since the only thin skin tissue might not be flexible enough.

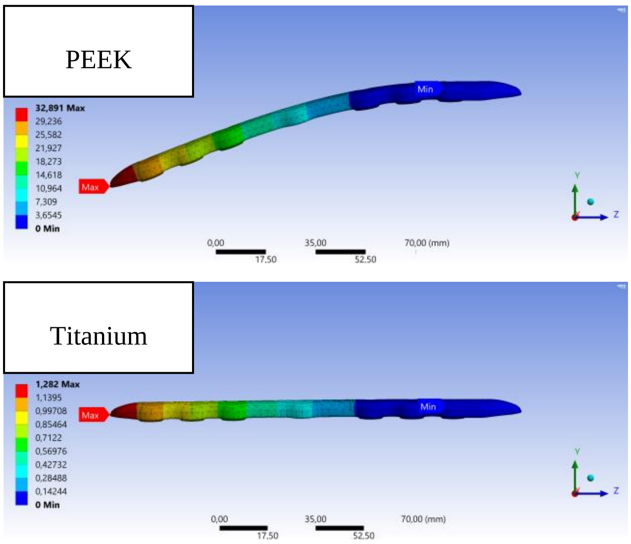

Figure 5: Overview of the deformation due to bending load case (50 N) in millimeter.

Also, the torsional stiffness is dependent on geometry factors and the shear modulus. The ratio between the shear modulus of titanium to PEEK is 27,7 which is the same ratio as the deformation between the titanium and the PEEK plate. The resulting difference is visible in figure 6.

To decrease the difference, also an increase of the dimensions is required. The direct impact of each change of the geometry would have to be calculated but the same changes as described for the bending stiffness would lead to an increased torsional stiffness. Therefore, improved torsional stiffness requires similar changes of geometry as described for the bending load case.

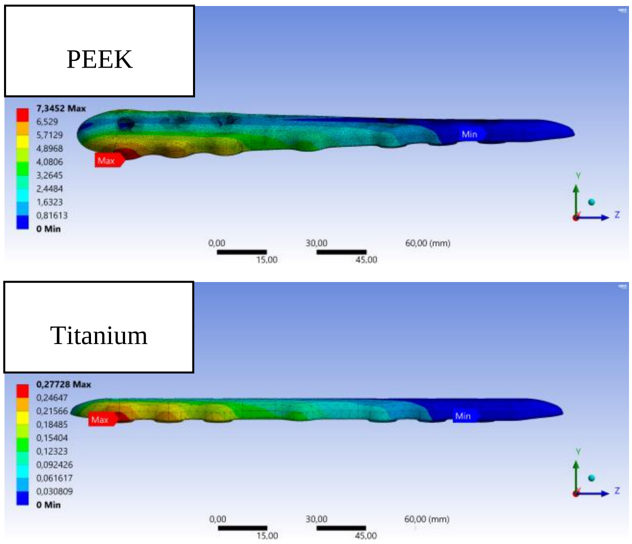

Figure 6: Overview of the deformation due to torsional load case (5 Nm) in millimeter.

The axial load leads to very small deformations but the deformations are also dependent on the mechanical properties.

Due to small changes, it`s not further discussed in the scope of this paper. The combined load case scenario leads to a superposition of the three other deformations. This can be seen in fig. 7 which also highlights the deformation differences between PEEK and titanium.

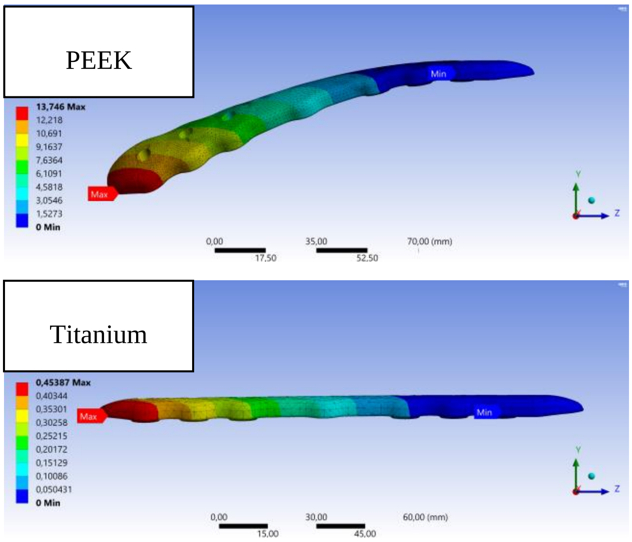

Figure 7: Overview of the deformation due to combined load case (5 Nm) in millimetre. Deformation is amplified by the factor of 3 to improve the visibility.

IV. Conclusions

Two generic, geometrically identical osteosynthesis plates which are applicable at the diaphysis were analysed. A comparison of a similar PEEK to a similar titanium plate leads to very different deformations while the stress distribution is equal in four typical load cases. Bending loads are leading to the highest stress and deformation, and by that have the strongest impact on the bone. This is followed by the torsion load case. Axial loads have only little impact on the plates while the combination leads to a stress and strains in between the torsion and axial load case.

Due to the lower yield strength of PEEK the stress would lead to permanent changes of the PEEK implant but not of the titanium implant. High deformation of the bone leads to delayed or failed healing processes – for PEEK plates the deformations are very high. The peek implants have to have notably larger dimensions or a changed geometry to reduce the effects presented. Stress shielding effects can only be reduced at the cost of higher fracture gap movement or by an implant with an increased size as more PEEK is needed compared to titanium when aiming for similar mechanical performance. This leads to a change in total volume occupied by the implant. This will influence the regenerative processes. Due to this PEEK implants lead to more soft tissue irritation and to less perfusion of blood and by that also negatively interfere with the healing process. Thus, they are not favourable over metallic implants if the implant is exposed to loads. This might be solved if the additively manufactured osteosynthesis plates would have new geometries which are better suited against torsional and bending load. The simulation results shown before can be used to adapt the design of additively manufactured implants to the critical loading scenarios and utilize the high degree of design freedom of this technology most efficiently. For now, PEEK is advantageous for osteosynthesis plates at locations which are only affected by weak mechanical loads due to the discussed benefits, e. g. better x-ray and MRI compatibility and reduced stress shielding effects. Furthermore, patient specific implants, e. g. for cranio-maxillofacial implants, which need a complex specific geometry for an optimal rehabilitation of the appearance of the patients [3] are another use case. This applies especially for autologous grafts. Other solutions could be improved mechanical properties, e. g. enhancement with carbon fibres, which is also discussed in literature [2]. Until this is solved, metallic implants will be favourable for mechanically loaded fractures.

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Author's Statement

Authors state no conflict of interest. Informed consent has been obtained from all individuals included in this study.

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