Journal of
Biomedical Engineering and Research

Research Open Access

Evaluation of Mechanical Properties in Titanium (Ti)-Based Pylon Component Upon Friction Stir Processing

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Received Date: October 01, 2016, **Accepted Date:** October 25, 2016 **Published Date:** October 27, 2016

Citation: Michael Frank (2016)Evaluation of Mechanical Properties in Titanium (Ti)-Based Pylon Component Upon Friction Stir Processing. J Biomed Eng 1: 1-8.

Abstract

A pylon device was theoretically and computationally analyzed with special focus on retaining mechanical strength and reducing the weight without compromising safety and performance. In this study, friction stir processing was applied on titanium (Ti)-6 aluminum (Al)-2 tin (Sn)-4 zirconium (Zr)-6 molybdenum (Mo) (or Ti 6246) – based pylon and compared against other pylon materials currently available on the market. The results show significant improvement of component strength upon friction stir processing. Additionally, results for a factor of safety show potential for design benefits and opportunity for weight reduction in pylon components with improved performance.

Keywords: Pylon; Biomedical components; Friction stir processing; Titanium alloys; Prosthesis

Introduction

Amputation is the partial or complete surgical removal of a biological limb or extremity. Most amputations result from vascular disease or diabetes mellitus. Approximately, 54% of amputations are caused by vascular diseases, 45% are caused by trauma cases, and the remaining are caused from cancerous medical conditions [1]. Statistical research shows that 55% of lower limb amputees will require amputation of the remaining biological limb in 2-3 years, significantly increasing the number of lower limb amputation procedures and prostheses [2]. In practice, the prosthesis has a total assembly weight less than that of the biological limb. The reason is due to the fact that if wearing a prosthesis with equivalent weight to that of the biological limb, the prosthesis can become an external load for the human body and it is unrealistic to expect that the amputee will wear the prosthesis for constant 8 hours period because of discomfort. Regardless of the design, a prosthetic limb is composed of three critical parts: the pylon, the suspension-socket system, and prosthetic foot as shown in Figure 1 below [4].

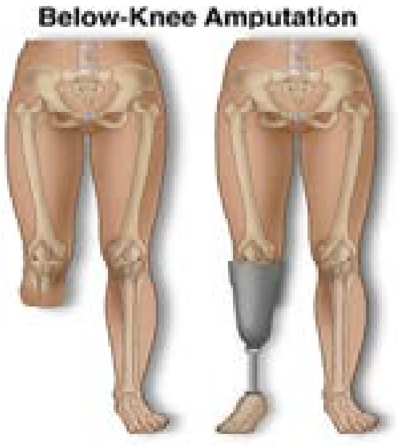


Figure 1: Schematic of prosthetic pylon design [4]

Figure 2 shows the most common cylindrical shaped pylon design used in prosthetics. The middle cylindrical shape is the pylon and the tube clamps are attached on each end (Figure 2).

Figure 2: Most common commercial prosthetic pylon design. Courtesy of Excell Orthotics and Prosthetics in Denton Texas.

The pylon shape, weight and interfacing methods are a few critical considerations which control the design of these components. The shape of the pylon would require features that could not potentially harm others or harm the amputee. The interfacing methods also deemed to be a challenge in the sense that most prosthetic components use a standard adapting method and for new designs to function as intended pylon standards need to be considered. Studies show that prosthesis weight plays an important role based on where it is positioned with respect to the segments of the leg [3,5]. Even though, the weight of the prosthetics depends strongly on the specific needs of the amputee, lighter weight platform for the lower prosthetic components remains a goal. Lighter weight will allow for more of the components used in the enhancement of the prosthesis to be added without having to compromise desired functional characteristics as defined by the amputee. This weight requirement sets the concept discussed in this feasibility study as a potential integration of alternative material and a manufacturing process to create a light weight pylon platform for some of these advanced prosthetics systems which will improve amputee quality of life.

Typical materials are Al or Ti - based alloys as most commonly used in pylon application. Manufacturers often will not disclose the composition or grade of aluminums used in their components so here just for comparison of properties between materials Al 1060, Al 6061, and Al 7075 were selected for evaluation. Ti6Al-4V is commonly used in these applications as well, and is comparable to Ti6Al-2Sn-4Zr-6Mo (our material of interest for this study) in terms of its strength relative to the aluminum alloys. Previous studies have shown that novel friction stir processing (FSP) has the ability to increase ultimate tensile strength of titanium (Ti) – based alloy (specifically Ti-6Al-2Sn-4Zr-6Mo) from typical values between 800 MPa and 1150MPa up to 2020 MPa [6]. Table 1 summarizes properties of friction stir processed Ti-6Al-2Sn-4Zr-6Mo against other common pylon materials.

Material	Material	Yield Strength (MPa)	Ultimate Strength (MPa)
Al 1060	84.99	27.57	68.94
Al 6061	84.83	55.15	124.08
Al7075-O	88.29	95	220
Ti6Al-2Sn-4Zr-6Mo (0.75 mm Thickness)	46.27	1048	1185.9
Ti6Al-2Sn-4Zr-6Mo (with FSP-0.75 mm Thickness)	31.08	1738	2020

Table 1 – Summary of properties of materials for pylon applications.

FSP uses a non-consumable rotating tool with a specially designed pin and shoulder. The rotating pin travels along the length of the material as shown shown in Figure 3.

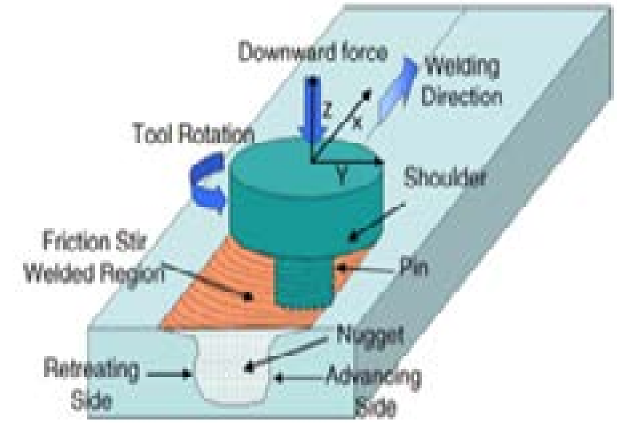


Figure 3 – Schematic of Friction Stir Process [7].

The rotating mechanism heats the work piece and micro-structurally modifies the material. The heat is generated by pressure which causes friction between the tool and work-piece, where plastic deformation occurs. Localized heating transforms the material to near liquid phase and allows the contacted material to be transferred from the front of the pin to its rear [7]. During FSP the material undergoes intensive plastic deformation resulting in generation of fine and equi-axed recrystallized grains. FSP does not involve filler metal so there is no additional weight added to the specimen and there are no necessary preparations of the specimen surface [7]. In this study we analyze titanium-based alloy material with friction stir processing as possible alternative for high stress regions in pylon device as a lighter in weight with increased strength solution. Titanium alloys are used heavily in biomedical applications due to their high strength-to-weight ratio and biocompatibility [8]. By incorporating selective FSP techniques in high stress regions of the pylon component, strength is increased while original physical properties and chemical composition are retained.

The results from this study present analyses of trans-tibial (i.e. below the knee) pylon design [9] with FSP regions and a goal of increasing weight rating by 10% while achieving an overall weight reduction and factor of safety between 1.2 and 3

Methods and Materials

Titanium 6246 was selected as the material to be used in this study. Ti 6246 is an alpha-beta alloy that can be heat treated to higher strengths compared to other titanium alloys. Advantages of Ti 6246 are: low modulus of elasticity (approximately 114 GPa or 16500 ksi) and thermal expansion, non-magnetic, good fatigue resistance, good high temperature mechanical properties, low density and superior high strength-to-weight ratio [6]. For this study we will use the experimentally obtained yield strength value of 252 ksi (or 1738 MPa) for friction stir processed titanium 6246 [6]. These experimental values are used to theoretically examine the feasibility of the proposed prosthetic pylon, with aims towards low weight, higher strength in areas prone to fatigue failure and approximation for theoretical infinite life design.

The friction stir processing set-up in our lab is restricted only to processing flat rectangular surfaces therefore, one of our constrains in this study among other things was to modify the pylon design so that FSP can be applied in high stress regions. The modified pylon design consisted of two plates with dimensions 8”x 2”x 1/8” and two rods with rectangular cross section, 1/4in in width (Figure 4a). Figure 4b shows a CAD model of the proposed pylon design integrated into leg prosthesis. Table 2 summarizes characteristics of our proposed pylon design against selected commercial pylons.

Product	Material	Length (mm)	Weight at 127mm (g)
Proposed Design	Titanium	127	0.057
A-500 XHD [10]	Carbon Fiber	304.8	0.098 – 41.8% difference from above
5209C [11]	Carbon	304.8	0.112 – 49% difference from above

Table 2: Summary of different pylon characteristics

It is evident that the weight of the proposed pylon in this study is lighter by at least 40% at standard length of 127mm compared to the commercial pylon models listed in Table 2. The components manufacturing for the proposed pylon was done following the three step process. First, rectangular plate with dimensions of 8” x 2” x 1/8” was friction stir processed in the middle using different processing parameters as shown in Figure 5 in order to determine the optimal set of parameters for friction stir processing of Ti. Table 3 summarizes parameters for each trial. After the several trials, the optimal processing parameters for titanium 6246 were in enclosed area in presence of argon at a spinning speed of 1000 rpm and travel speed of 1 in/min.

a) b)

Figure 4: a) Image showing the proposed pylon design b) CAD model showing proposed pylon design fully integrated into the prosthesis system

Figure 5: Trial FSP of Ti 6246 plate in order to determine optimal processing parameters

Trial #	Spinning speed (rpm)	Travel speed (in/min)	Environment
5, 4 & 3	600	1	Air
1, 2	1000	1	Air
6	1000	1	Argon

Table 3 – Summary of processing parameters for each trial in Figure 5

By introducing argon as a shielding gas into the closed area, titanium 6246 will not oxidize resulting in an improved quality of the material's surface. Next, four plates were cut on the water jet cutter in a shape shown in Figure 6. Figure 6a shows CAD model and Figure 6b shows the plates extracted after water-jet cutting. Tolerances were set to +/- 0.002 to achieve best fit between parts. Across each cut plate there is a FSP region as shown in Figure 6b. Those are the high stress areas prone to failure due to fatigue. Last, press-fit technology was used as a method to assemble the different parts together and make them a final product as shown in Figure 4a. This coupling portion of the assembly required for a press fit between the two supporting members and the top and bottom plates. Each supporting member received was within acceptable tolerance range, ensuring the components would not be provided with an undersized cross section. The members were required to be subtlety grinded on each corner of either end at a depth of 1/8" to provide the desired fitting. A bench grinder with an aluminum oxide wheel was used to abrade surfaces and provide a radius at the corners of the members. The plates were then forced, under constant applied pressure, into the intended interfacing position to ensure a complete coupling.

a)

b)

Figure 6 – a) CAD model showing the four plates for the proposed pylon design b) image showing four plates cut on the water-jet

Engineering Analysis

The experimental data from yield stress along with several engineering analyses performed has guided our proposal for an improved pylon model. The analyses were performed by simulation and control of stress, strain and displacement data. An equivalent Von Mises stress (σ_v) was calculated using equation 1 where σ_(1) and σ_2are principle stresses [12]. The Von Mises stress value serves as an operating stress when calculating the factor of safety while the experimentally obtained yield stress (σ_y) will be the maximum stress permitted that the model can undergo; the ratio between the two is the factor of safety (Fs) as presented in equation 2 [12]. Design load (P) was estimated as product of the factor of safety and the anticipated load as given in equation 3. Values for Young's modulus are calculated as function of stress and strain using Hook's Law [12].

$$\sigma_v=\sqrt{}(1/2[\sigma_1{}^2-\sigma_1\,\sigma_2+\sigma_2{}^2+3\sigma_2{}^2]) \quad \text{Eq.(1)}$$

$$Fs=\ \sigma_y/\sigma_v \qquad \text{Eq.(2)}$$

$$P=F_S{}^*\text{Anticipated Load} \quad \text{Eq.(3)}$$

Another critical parameter from engineering point of view for pylon structures is critical buckling load which however, in current designs is not evaluated and remains standard in terms of dimensioning. Therefore, in this study we follow Euler's buckling theory [13] to estimate the buckling critical load and for purpose of this study buckling is considered failure in the static conditions. The critical buckling stress is defined by calculating the theoretical buckling load (PCr), with cross-sectional area (Ax) as defined by equations 4 and 5 where C is an end condition constant, E is elastic modulus, and I is moment of inertia. Defining this stress was a method of being more critical to failure in the structure, specifically to prevent failure before yielding as shown in equation 6, nodal to critical stress ratio(β). Figure 7 shows buckling of beams with various end conditions. For analysis in this study the pylon model was treated as a beam with one fixed end while the other end distributed forces were applied, where the load varies between 250lbs to 600lbs.

$$\text{Critical Load,}P_{Cr}=(C\pi^2\,EI)/l^2 \qquad \text{Eq.(4)}$$
$$\text{Critical Stress,}\sigma_{Cr}=P_{Cr}/A_x \qquad \text{Eq.(5)}$$
$$\text{Nodal to Critical Stress Ratio,}\beta=\ \sigma_{nodal}/\sigma_{Cr} \quad \text{Eq.(6)}$$

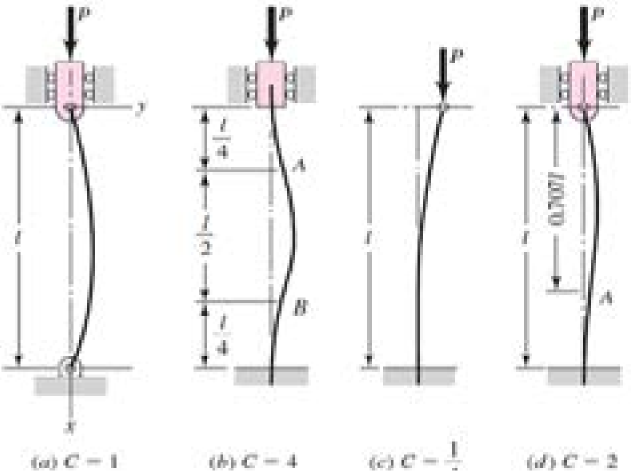


Figure 7: Euler Column Buckling: End Conditions Constant Schematic [13]

Modeling Approach

Simulation were performed using the finite element analysis packages (FEA) SOLIDWORKS and ANSYS. The main function of the assembly is to withstand the loads applied by the amputee and provide a comfortable and natural movement. With this function in mind, considerations of failure modes are driven by the forces that are applied. More specifically, the level of the forces and the orientation that these forces are applied are considered in this study. Although the device may behave properly throughout the testing phase at a laboratory scale, additional factors that may cause the assembled system to not perform properly should be considered. Not only can malfunctions cause the device to perform poorly but they can also create significant safety hazards for the host. Factors like possible degradation of the stability of the system after cyclic loads are therefore also considered in the failure analysis exercise. During use of the pylon, even the loads significantly below static limits can cause failure if the load is repeated sufficient amount of times. While the dual bar pylon may sustain static loads successfully, the design was required to also withstand extreme cyclic loading conditions. Fatigue analysis characterizes the capability of a material to survive the many load cycles a component may experience during its lifetime. The ANSYS Fatigue Module provides a fatigue life analysis tool that illustrates the behavior of a model with a certain load applied over a period of time. The software finds fatigue by three main methods: Strain Life, Stress Life, and Fracture Mechanics. Stress Life is concerned with total life and does not distinguish between crack initiation and propagation. The aim here is to test for cyclic loading above 10^6 cycles. In terms of cycles, Strain Life usually deals with low number of cycles and addresses Low Cycle Fatigue (LCF). The cycles incorporated in LCF are fewer than 10^5 cycles. Stress Life conventionally deals with high numbers of cycles and addresses High Cycle Fatigue (HCF). The cycles incorporated in HCF are greater than 10^5 cycles inclusive of infinite life (Browell). The design of the dual bar pylon is intended to avoid potential failure due to cyclic loading. Testing the prototype under HCF can provide simulated results that imply that the proposed prosthetic component will withstand fatigue when in use by a patient. Therefore, finding fatigue by Stress life corresponds with the needs of this study. Stress Life is based on S-N curves (Stress – Cycles curves). Total Materia provides an online database of material properties. From this database the standard alternating stress data for Ti-6Al-2Sn-4Zr-6Mo was obtained that is required in order to operate the Fatigue Module in ANSYS. Figure 8 shows the information being imported into the engineering data library of Workbench. From the MatWeb online database physical properties were acquired for Titanium 6246, which were incorporated into Workbench and merged with the mean stress data obtained from Total Materia.

Following the guidelines by Raymond Browell and Al Hancq on Stress Life several aspects are considered in order to accurately analyze fatigue results in devices [14]. Every decision can affect the outcome of the fatigue analysis in both predicted life and types of post processing available.

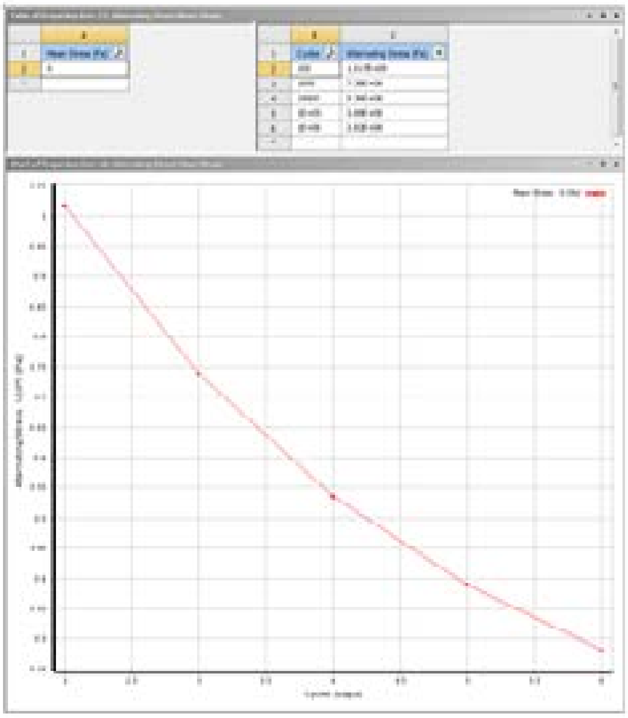


Figure 8: Alternating stress vs. cycled data imported into ANSYS Workbench.

The geometry of the proposed pylon design was produced in ANSYS (Figure 9a) and meshed into elements (Figure 9b). The model was created as a single body and uniform mesh parameters were prepared for the model. The element size for the mesh was 1.6mm with an A/B ratio held at 1.5, generating about 97,000 elements in the model. Boundary conditions were imposed on the structure by fully constraining the bottom (shown in green color) and applying distributed force on the top (shown in purple color) as shown in Figure 9c. The high stressed regions were processed with FSP and material properties listed in Table 1 were applied to this regions.

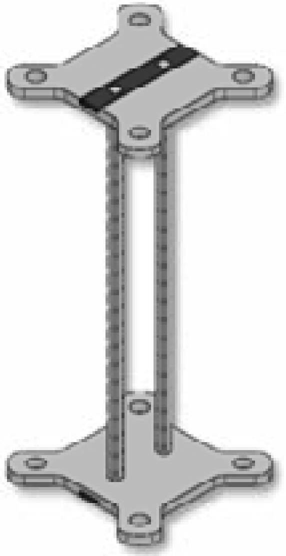
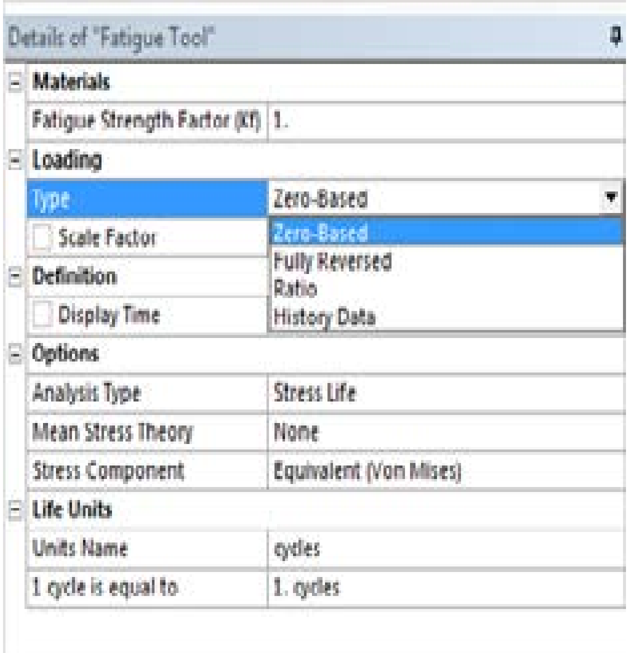


Figure 9 a) ANSYS 3D model of the proposed pylon

Figure 9: b) Meshed model in ANSYS

Figure 9: c) Boundary conditions imposed on the pylon design for modeling analysis.

Loading on this structure was implemented as fully reversed with zero based constant amplitude. Fully reversed loading means that stress variation is such that the mean stress is zero and maximum and minimum stresses are equal to mean stress. Comparing the simulation results of different loadings allows a better understanding of the performance of the design over its time in service. One simulation was performed with the "Zero-Based" option and a second calculation with "fully reversed". A picture of the software interface where options are selected is shown in Figure 10. After selecting the type of fatigue analysis and the loading type the next step is to apply a mean stress correction. Cyclic fatigue properties of a material are often obtained from completely reversed, constant amplitude test. If the loading is other than fully reversed, a mean stress exist and may be accounted for by using a Mean Stress Correction. Mean stresses can be accounted for directly through interpolation between material curves if experimental data at different mean stresses or ratio's exist.



Details of "Fatigue Tool"

Materials	
Fatigue Strength Factor (Kf)	1.
Loading	
Type	Zero-Based
☐ Scale Factor	
Definition	
☐ Display Time	
Options	
Analysis Type	Stress Life
Mean Stress Theory	None
Stress Component	Equivalent (Von Mises)
Life Units	
Units Name	cycles
1 cycle is equal to	1. cycles

Figure 10: Loading options under Fatigue tool in ANSYS Structural Modeler

If experimental data is not obtainable, empirical options like Gerber, Goodman and Soderberg theories can be used to find any mean stress [13]. These theories use static material properties (yield and tensile strength) and the S-N data curve. Most experimental data falls between Goodman and Gerber theories. Gerber theory is best choice for this study since it works better with ductile metals when compared to Goodman [13].

Results and Discussions

The next step will be to perform fatigue simulation analysis and generate results that will point towards high stress regions adequate for friction stir processing. The design in this study targeted factor of safety of at least 1.3, with a load between 250lbs - 600lbs placed on one end, where numerical calculations were performed and are summarized in Table 4. It is evident from the calculations that the model performed as expected, with a factor of safety above 1.3, when material properties of FSP titanium were considered. This will allow to develop physically stable pylon components and test them experimentally using feedback from the modeling approach.

Load		Pressure		Euler Alternating Stresses		Safety Factor
Lbs	N	Pa	Psi	Min	Max	Min
600	2669	291,192	42.2	19.6	1.4 e8	1.96
550	2224	266,926	38.7	17.9	1.3 e8	2.14
500	2002	242,660	35.2	16.4	1.2 e8	2.35
450	2002	218,394	31.7	14.7	1.1 e8	2.61
400	1779	194,128	28.2	13.1	9.6 e7	2.94
350	1557	169,862	24.6	11.5	8.4 e7	3.36
300	1334	145,596	21.1	9.8	7.2 e7	3.92
250	1246	121,330	17.6	8.2	5.9 e7	4.71

Table 4 : Summary of Fatigue Analysis

Figure 11 shows the stress distribution in the pylon model for 550 lbs force where the highest stress concentration occurs in the regions at the top plate of the pylon. These are the regions where friction stir processing is applied in order to decrease stress and improve durability.

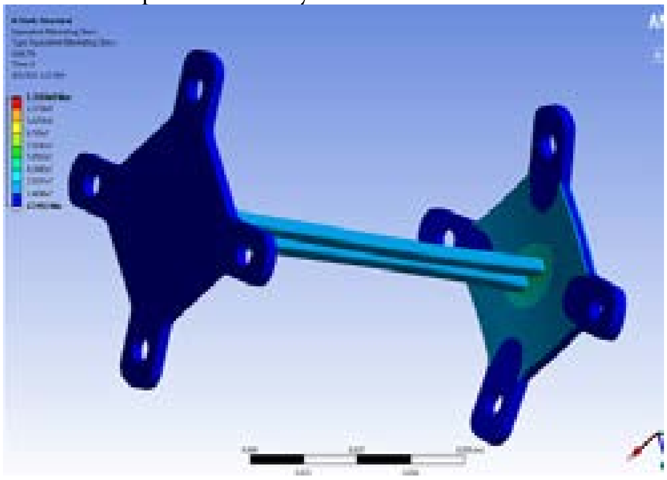
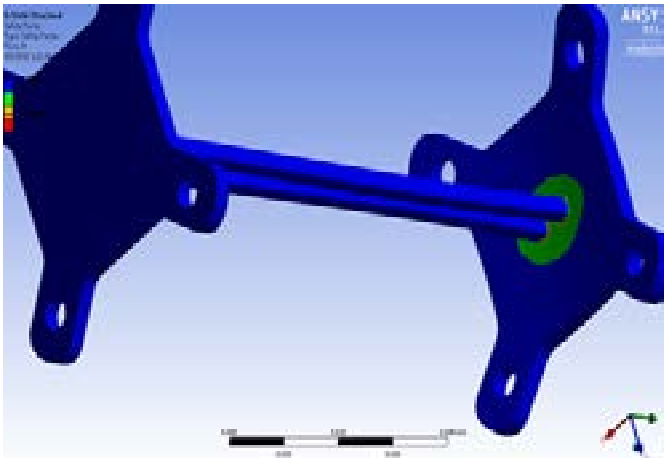


Figure 11 – Stress distribution in proposed pylon model simulated in ANSYS

Figure 12 shows Factor of Safety distribution for 550 lbs cycling loading. Minimum Factor of Safety is 2.139, average is 10 and maximum goes up to 15 as given in Figure 12.



From the simulation results of the ANSYS Fatigue module, we can estimate that the pylon will not reach failure due to fatigue even with an applied load of 550lbs. In the physical model the high stress areas have been identified and will be targeted with friction stir processing to increase strength of those critical areas. Further, the middle vertical members of the proposed pylon design were analyzed for buckling as mentioned in the Materials and Methods section. The proposed design encompasses two supporting members that mimic the function of structural columns. With this comparison, similar analysis was carried out to ensure the structural stability of the assembly. The Euler Buckling analysis takes a look at critical loads and ultimately critical stresses that will allow for buckling. It provides the maximum load and stress levels that will cause the columns to collapse. In the proposed design, there is the case of a long slender column, in which buckling then depends not only on the yielding strength of the material but also on the isotropic stiffness of the material.

Figure 13 shows buckling analysis data for each slender bar and relates the geometry of the material with the stiffness, and elastic modulus to provide the theoretical buckling stress for each supporting member. From the analysis in Figure 13 it is evident that the critical load is equally distributed between the two supporting members another evidence of optimal design with improved strength.

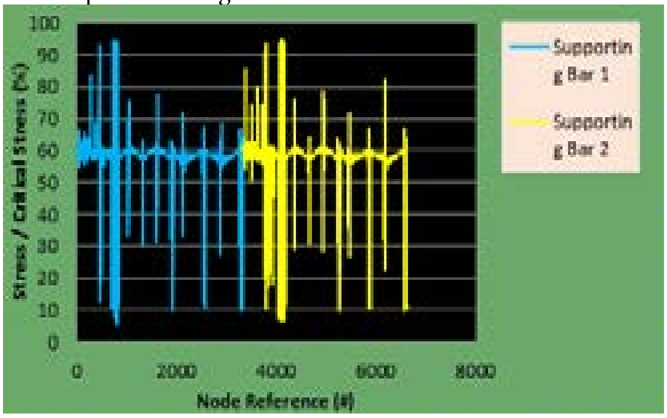


Figure 13: Euler Buckling Analysis for each slender bar in the proposed pylon design

Conclusion

The goal of this study was to evaluate FSP and seek feasibility in the use of it on cylindrical surfaces for biomedical applications and also to depict feasibility in a medical device that takes advantage of the increase in mechanical properties due to FSP. A prosthetic pylon was designed achieving an overall weight reduction and Factor of Safety (FOS) greater than 2. The proposed design achieved the targeted goals through simulated analysis. The ultimate loads applied generated stresses below the yielding and buckling limit which provided an overall factor of safety within our acceptable ranges intended for a patient experiencing loads from 400-600 lbs. The assembly weight before including modular adapters reached 57.22 grams, which was below currently marketed carbon fiber tubes rated to a lower weight capacity and of the same length, thus the rated strength to weight ratio goal was achieved. Fatigue analysis showed that the design would achieve a theoretical infinite life by forecasting the ability to withstand more than 106 cycles, while producing a safety factor of 2.35 with a 500 lbs load. Friction stir processing (FSP) high stress regions to ensure structural integrity is preserved in light weight applications involving Titanium 6246. FSP is a feasible opposition to adding additional material to strengthen those locations. This study shows strength achieved by FSP can increase local factors of safety and a theoretical extension of life of a design under cyclic loading analysis. This process is feasible not only for the lower limb prosthetics, but could also be considered for other endoskeletal, exoskeletal and even implant applications. The use of this process in the biocompatible titanium material would provide strong and light components for multiple applications. The titanium-FSP combo analyzed in this study serves as an initial step in solving the issues in the prosthetist's selection of a strong and light weight pylon component and can be considered by manufacturers as a platform for more complex electromechanical or pneumatic based lower limb prosthetics.

The processed specimens are ultimately improved to allow a reduction in weight while still preserving its original physical endurances, most importantly mechanical strengths. This concept can be applied to prosthetic components to enhance mechanical properties locally to provide the option to remove excess material to create a "lean" design in terms of weight while increasing the life of structures and components due to fatigue. Future targeted design is expected to withstand loads of standardized ISO 10328 P5 testing requirements [15]. These prerequisites are of the maximum levels of testing for lower limb prosthetic components. Future components must all be rated to withstand these rigorous tests so the ratings of all materials should provide proper support. Prosthetics today consider coupling the components to provide comfort and support for the amputee in parallel. Creating a design that provides the amputee with these traits is difficult and improving these traits goes beyond the scope of this paper. Studies of the expected results were structurally measured using simulations, providing only a confirmation of concept feasibility for a recommendation and further research in this area.

Acknowledgements

This work was supported by internal funds from UNT and Center for Friction Stir Processing (CFSP) at UNT. Authors would also like to thank members of Center for Friction Stir Processing (CFSP) for valuable discussions and providing various technical expertise and tools that made this work possible. Authors would like to thank Mr. Alex Gallegos, and Mr. Kaongou Temedjong for assisting with several aspects of the experimental part of this work.

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