DESIGN OF NOVEL AGGRESSIVE DENTAL IMPLANT WITH INCREASED SECONDARY STABILITY

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

Master of Technology
in
Production Engineering

by
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Production Engineering
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May, 2023

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CANDIDATE'S DECLARATION

I, Dhruv Batra, Roll no. 2K21/PRD/03 of M.Tech (Production Engineering), hereby declare that the project Dissertation titled "DESIGN OF NOVEL AGGRESSIVE DENTAL IMPLANT WITH INCREASED SECONDARY STABILITY" which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: Delhi

Date: May 31, 2023

DHRUV BATRA

DEPARTMENT OF MECHANICAL ENGINEERING

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CERTIFICATE

I hereby certify that the project Dissertation titled “DESIGN OF NOVEL AGGRESSIVE DENTAL IMPLANT WITH INCREASED SECONDARY STABILITY” which is submitted by Dhruv Batra, Roll no. 2K21/PRD/03, Department of Mechanical Engineering. Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

Date: May 31, 2023

Prof. Qasim Murtaza

SUPERVISOR

Professor,

Department of Mechanical Engineering,

Delhi Technological University

ACKNOWLEDGEMENT

It would be false to assume that this project work could have been completed by me without requiring external academic help.

I express my gratitude to a number of people starting with all the researchers whose research work have been referred in order to complete this project. Without their pre-existing research articles, it would take me much longer to complete the project. My supervisor Prof. Qasim Murtaza has my heartfelt respect in helping me throughout the span of the year. I express my appreciation for Dr. Rajat Sehgal and Dr. Alok Batra for their unending academic dental expertise without which an interdisciplinary project like this would never have been a success.

Also, I would like to thank Delhi Technological University for providing with the access of numerous research journals without which the completion of this design would only be a dream.

DHRUV BATRA

ABSTRACT

The objective of the following research is to design an aggressive dental implant which will have higher secondary stability than its existing counterparts. Secondary stability in dental implant is the result of new bone formation due to flow of blood which carry osteocytes in regions where contact between bone and implant is established. The only way to increase secondary stability of a dental implant is by increasing bone-implant contact area. In the following research, use of additive manufacturing and geometric modifications have increased the bone-implant contact area.

LIST OF FIGURES

NOMENCLATURE

- ISQ: Implant Stability Quotient
- BICA: Bone implant Contact Area
- SL-AW : Hydroxyapatite/b-tricalcium phosphate mixture blasting and after acid washing (according to ASTM F-86 procedure)
- SL : Hydroxyapatite/b-tricalcium phosphate mixture blasting
- RBM : Biphasic calcium phosphate blasting
- MA : Anodization in an electrolytic solution with an acidic character at 300 V for 5 minutes
- SL-MA : Sandblasted with hydroxyapatite/b-tricalcium phosphate mixture; sandblasted with an acidic character at 300 V for 5 minutes after anodization in an electrolytic solution
- DMLS: Direct Metal Laser Sintering
- mm: millimeter
- µm: micrometer

CONTENTS

CHAPTER 1 – INTRODUCTION

1.1 History of Dental Implants

Dental implantology has experienced major developments in the past century. As a result of Dr. Per-Ingvar Branemark's discoveries of osseointegration in the 1950s, titanium implants were developed. Implant design, surface modifications, and surgical methods all dramatically improved in the next decades. In the 1990s, a variety of implant systems with adaptable characteristics became available. The development of CAD/CAM technology increased precision and eased implant surgery. Recent years have seen an array of advancements such as 3D imaging and rapid loading techniques in addition to digital dentistry. Research is still being done on materials, surface coatings, and healing methods. Today's dental implants offer a long-lasting, visually appealing, and practical tooth replacement option. The development of dental implants over the past 100 years has been amazing, and the future prospects in providing the best care for people who need to replace their teeth look bright.

1.2 Osseointegration

The longevity of oral implants is largely attributable to the fundamental process known as osseointegration, which transformed the field of implant dentistry. It refers to the both the physical and functional link between the implant surface and the bone tissue that is presently developing. Dental implants have to undergo osseointegration to achieve stability over time, resilience, and functionality.

Dr. Per-Ingvar Branemark, a Swedish orthopedic surgeon, first suggested the idea of osseointegration in the 1950s. Branemark made a remarkable finding while performing research on the reconstruction and regeneration of bones. He discovered that bone tissue and titanium, a biocompatible metal, could bond when in close contact. The conventional wisdom that metal could not integrate with live bone was debunked by this ground-breaking finding.

When a dental implant, typically made up of titanium, is surgically inserted into the jawbone, the process of osseointegration commences. For it to provide the best possible connection between the implant surface and the surrounding bone tissue, the implant is carefully positioned and placed in the bone. After placement, a healing phase known as the osseointegration phase follows.

The implant serves as an alternative for a tooth root during osseointegration, offering support for the restoration that will be placed on top. Bone cells come into contact with the implant surface, which fosters their association and growth. Bone cells eventually start to adhere to the implant surface and form a solid attachment.

Several essential factors must exist for osseointegration to be accomplished. The material of the implant, preferably titanium, must be biocompatible. Excellent physiological compatibility with titanium minimizes the risk of rejection or negative reactions. The osseointegration process is additionally affected by the implant surface characteristics, namely texture and topography. Acid etching or plasma spraying of the implant's surface may enhance the implant's ability to osseo-integrate.

The duration of the osseointegration period varies according to each individual's ability for healing, the position of the implant, and other factors. Osseointegration typically takes several months to complete. The patient might put on a temporary prosthesis during this time to restore both its appearance and its function.

1.3 Primary and Secondary stability

Primary implant stability is well recognized as a critical aspect in the effective osseointegration of dental implants. There is enough evidence to acknowledge a favorable association between primary implant stability and implant success, because implant success is dependent on the implants' long-term integration into hard and soft tissues. Secondary stability is influenced by primary stability and has been shown to improve four weeks after implant placement. As a result, a stability gap with the lowest implant stability is expected in the first 2-3 weeks after implant placement.

CHAPTER 2 – LITERATURE REVIEW

2.1 Thread morphology for primary stability

The "implant stability quotient" (ISQ) is a statistic used to gauge the level of stability and osseointegration in dental implants. The scale ranges from one to one hundred, with greater values indicating greater reliability. Research done by Yamaguchi et al. [1] suggests that in the given 3 samples 12S, 06D and 06S, best ISQ of 55.66 ± 1.62 is achieved by the 06S implant. Hence, morphology similar to thread 06S was considered ideal for higher primary stability. Primary stability is critical in dental implants as it directly impacts the implant's success and long-term prognosis. It refers to the very initial mechanical stability achieved following implant insertion. Sufficient primary stability means the implant is securely anchored in the bone, providing for good osseointegration. Implant design, surgical technique, bone quality, and implant-bone interface are all factors that contribute to primary stability. Primary stability is essential because it endorses natural healing and prevents micromovement, which could postpone osseointegration. It offers a sturdy basis for functional loading and lowers the chance of implant failure. It is critical to assess and enhance primary stability during implant placement in order to offer predictable and successful outcomes in implant dentistry. This proved that single thread designs provide for better primary stability.

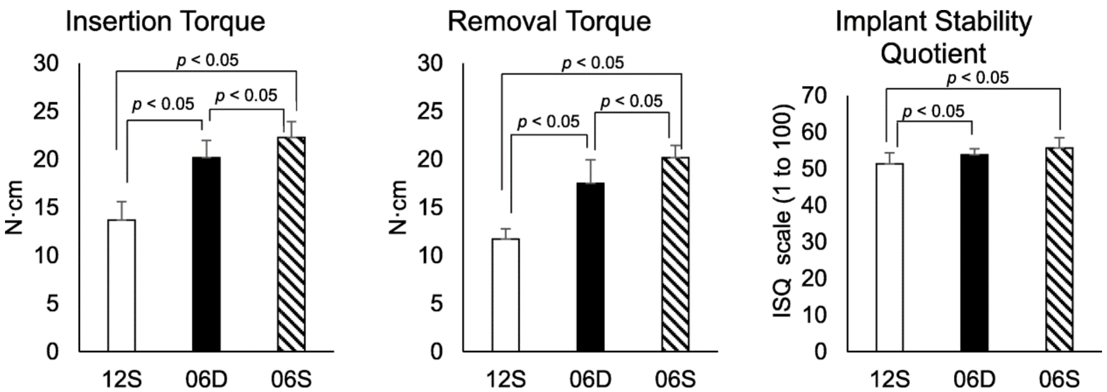

Figure 1 Comparison of three different thread designs with respect to ISQ

2.2 Importance of primary and secondary stability

According to the research done by Muhamad et al.[2], after implant insertion, mechanical stability is typically quite high (primary stability). This happens when the implant is put in because the bone is mechanically compressed, and it gets smaller over time. On the other hand, biological stability is absent right away after installation. It is only noticeable once fresh bone cells start to grow at the implant site, and it gets stronger over time (secondary stability). Biological stability is added to or replaced by initial mechanical stability as a result of osseointegration, and the final stability level for an implant is the total of the two. Generally speaking, stability changes following implant implantation. For instance, as the implant becomes biologically stable, stability is anticipated to initially decrease and then rise.

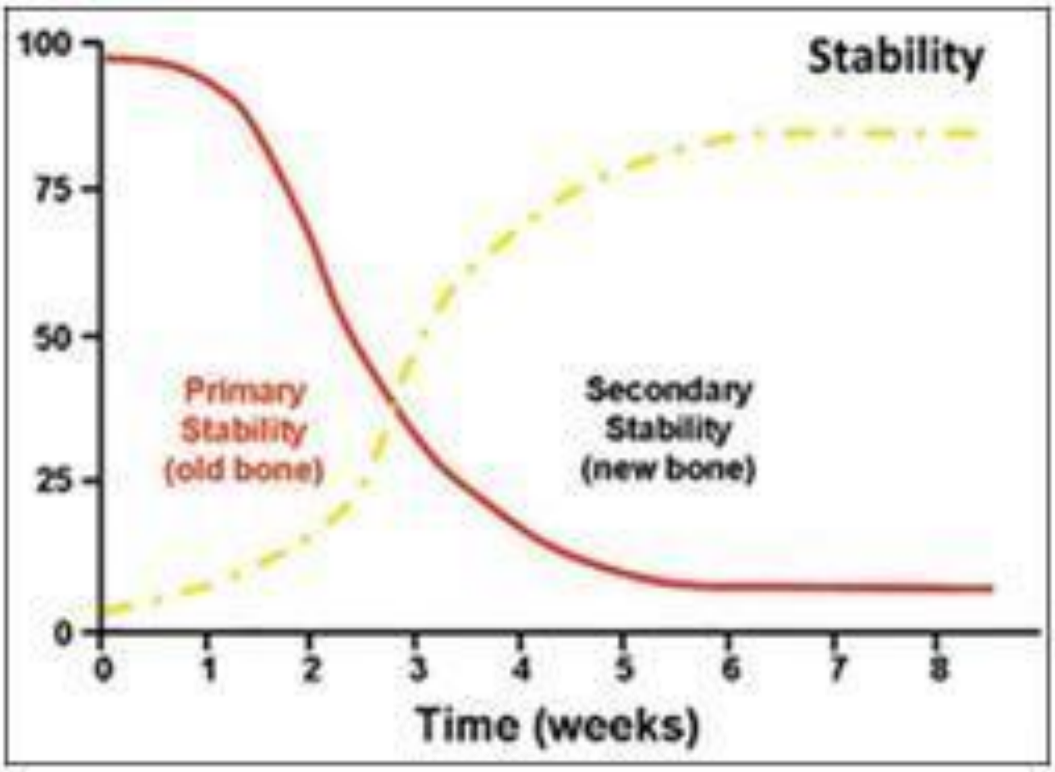

Figure 2 Primary versus Secondary stability with respect to time

2.3 Comparison of roughness of different implant surfaces

Research done by Dunder et al.[3] suggests the following surface roughness values for multiple surface treatments methods for Ti6Al4V used in dental implantology.

- SL-AW group: 1.674µm

- SL group: 1.617µm
- RBM group: 1.652µm
- MA group: 0.423µm
- SL-MA group: 1.133µm

Research done by Ishfaq et al.[4] shows surface roughness values of Ti6Al4V processed using DMLS technology to be in the range of 8 – 25 µm.

2.4 UV Radiation, Calcium Modification and Sandblasting

Processes such as sand blasting implant surface increases surface roughness in turn increasing osseointegration. Treatment under UV radiation ionizes the titanium which increases its ability absorb fluids. Calcium modification results in easier connection between titanium and bone.[5][6][7]

2.5 Relation between BICA (bone implant contact area) and secondary stability

A significant variable that impacts secondary stability is the bone-implant contact area (BICA). It indicates the extent to which of the implant surface is in direct contact with the surrounding bone. A greater surface area for bone integration is provided by a bigger BICA, which makes it easier to pass on functional loads to the surrounding bone. A more significant osseointegration is favoured by the larger contact area, which increases the secondary stability of dental implants. Several factors influence the BICA and, consequently, the secondary stability of dental implants. Among the key factors are implant design, surface characteristics, surgical technique, and bone quality. The BICA can be affected by implant design characteristics such as thread design, surface roughness, and macro/micro-geometry. Increased BICA and increased mechanical interlocking are aided by a rougher implant surface.

For the effectiveness and endurance of dental implants, the BICA has important clinical consequences. Increased secondary stability brought on by a greater BICA lowers the likelihood of implant failure and increases long-term implant survival rates. It increases the implant's capacity to tolerate functional stresses, reducing the risk of implant movement and peri-implant bone loss. Furthermore, higher BICA helps divide loads more uniformly, decreasing stress surrounding the implant, while promoting positive remodeling of the bone.

2.6 Research Gap

2.6.1 The reviewed articles fail to DMLS technology with dental implants.

2.6.2 No major geometric changes were made except modifying thread morphology. Geometric changes to increase BICA were absent.

2.7 Research Objective

2.7.1 Geometric modification in the implant body to increase BICA which will further increase secondary stability

2.7.2 Changing the manufacturing from subtractive to additive in order to obtain coarser surface hence increasing BICA at micro level.

2.7.3 Material used for this implant is Ti-6Al-4V

CHAPTER 3 – RESEARCH METHODOLOGY

3.1 PRELIMINARY MODELLING

- Most demanded industry specifications are chosen resulting in upper diameter of 4.2mm and length 11.5mm. Lower diameter of 2.1mm is taken.
- Using the above written dimensions, a taper cylinder was modelled.
- Cylinder was divided into three parts along the axis with length ratios 20%, 50% and 30%.
- Three separate helical profiles were drawn in these three sections with number of rotations being 5,5 and 3 respectively.
- Material used for this implant is Ti-6Al-4V

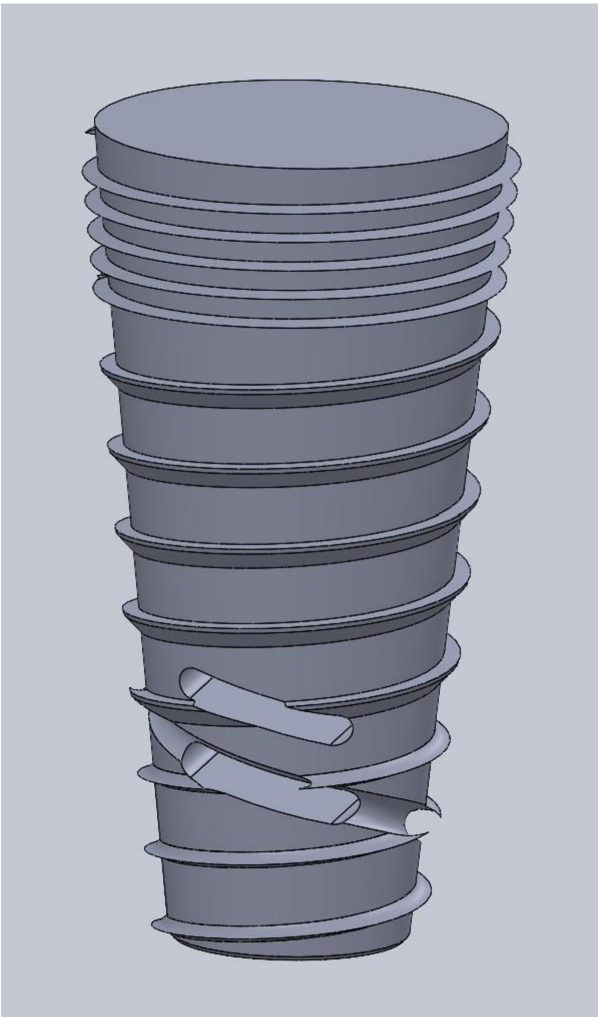

Figure 3 Dental Implant: Outer Structure

3.2 Thread morphology

- Thread depth was taken as 0.2mm in all three cases[8].
- The topmost cortical thread section was given V-thread.
- The middle section consists of buttress thread.
- Bottom most thread consists of modified V-thread.

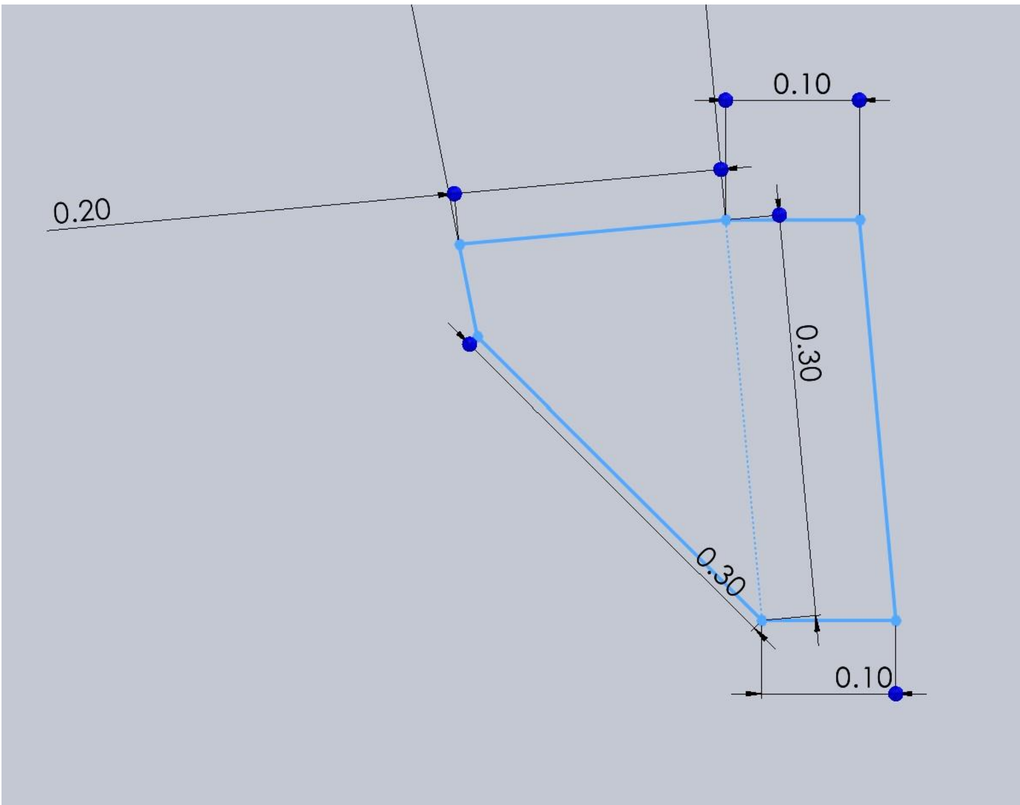

Figure 4 Thread Morphology: Buttress

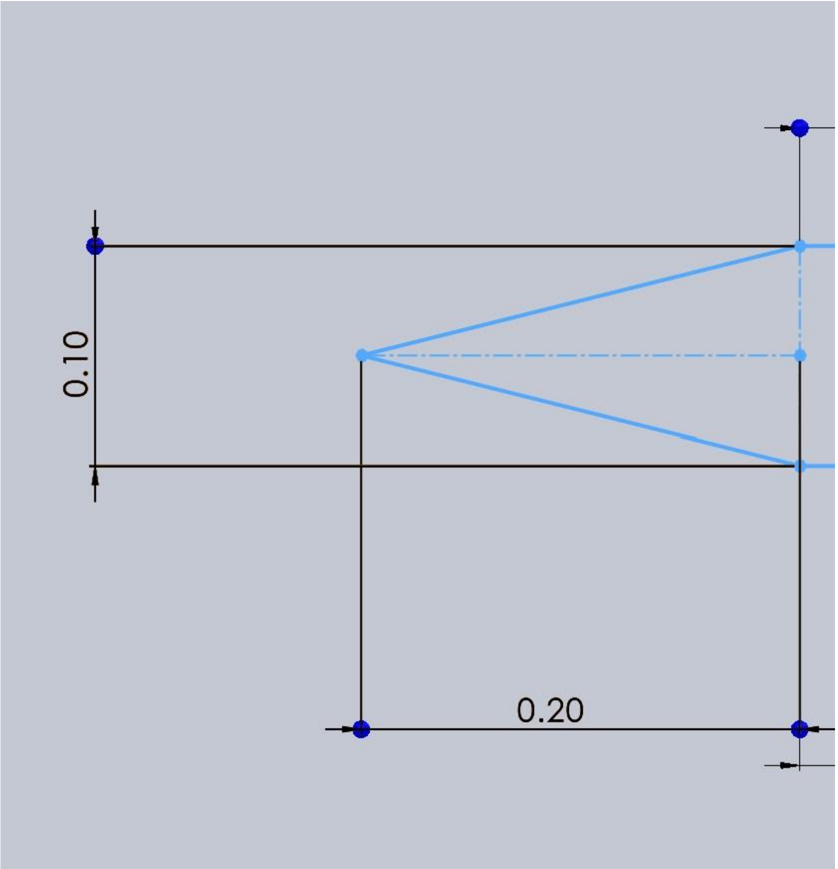

Figure 5 Thread Morphology: Cortical thread

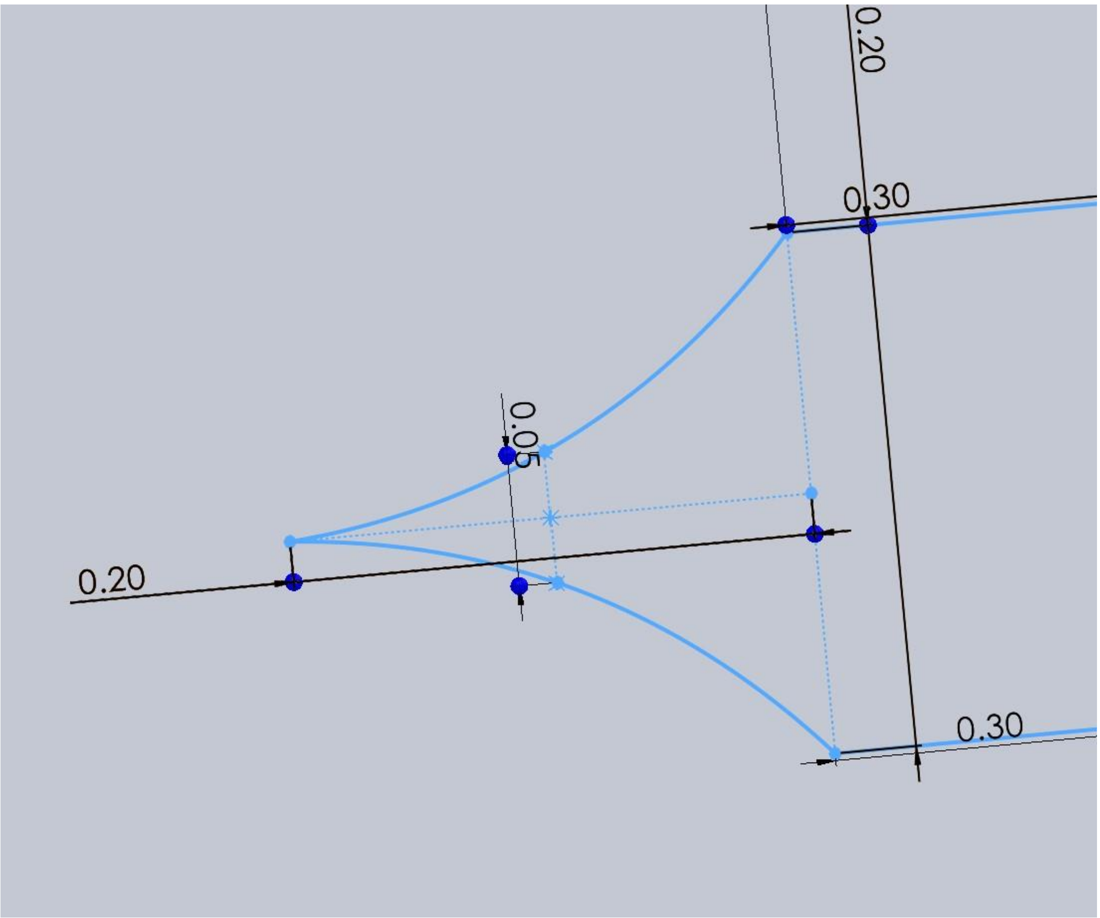

Figure 6 Thread Morphology: Cutting thread (modified V)

3.3 BICA modifications

3.3.1 Geometric modification

Two slots of the following dimensions were cut laterally in the implant.

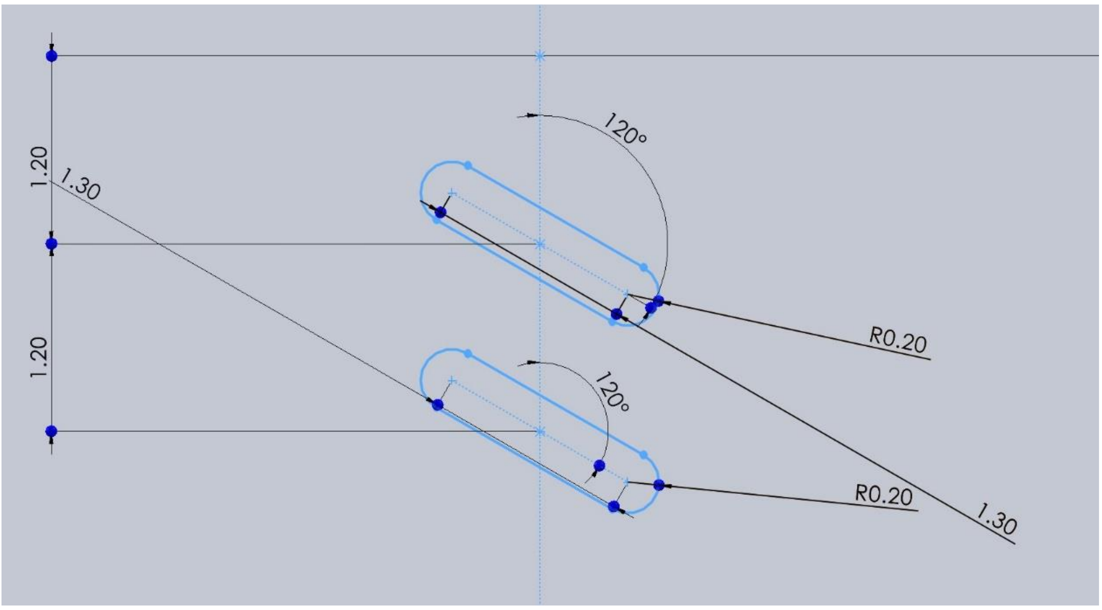

Figure 7 Slot Design

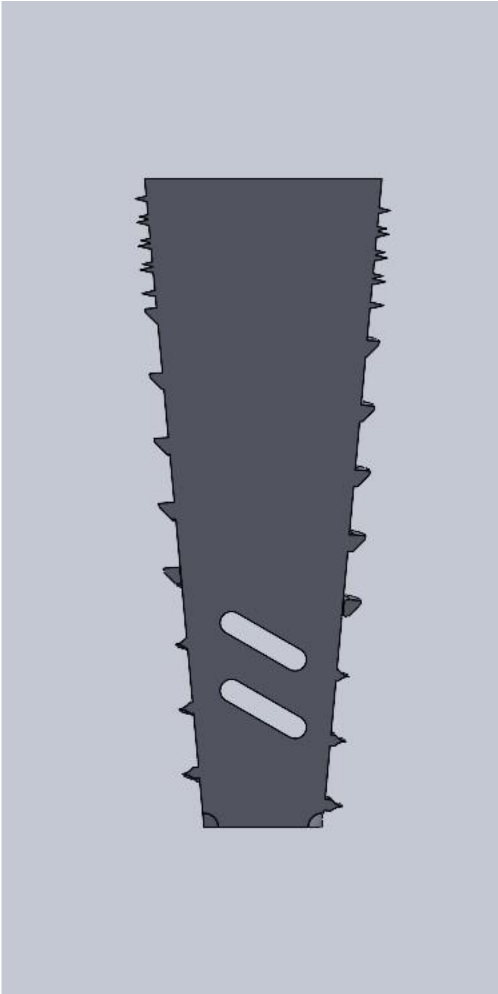

Figure 8 Cross sectional view of dental implant

- BICA of the slot area before cutting is 0.6456mm^2
- BICA of the slot area after cutting is 9.61mm^2
- BICA due to slot in that region increased up to 14.88 times.

3.3.2 DMLS for manufacturing

- Surface roughness provided by DMLS is 25µm
- Rough surface would increase the surface up to 2 times.

3.4 Static Structural Analysis

Material used for this implant is Ti-6Al-4V

NOTE: Relevant analysis for <u>von-Misses stress, deformation and factor of safety</u> were done. Detailed report is attached in the appendix.

CHAPTER 4 – RESULTS

Maximum deformation observed is 0.6 microns

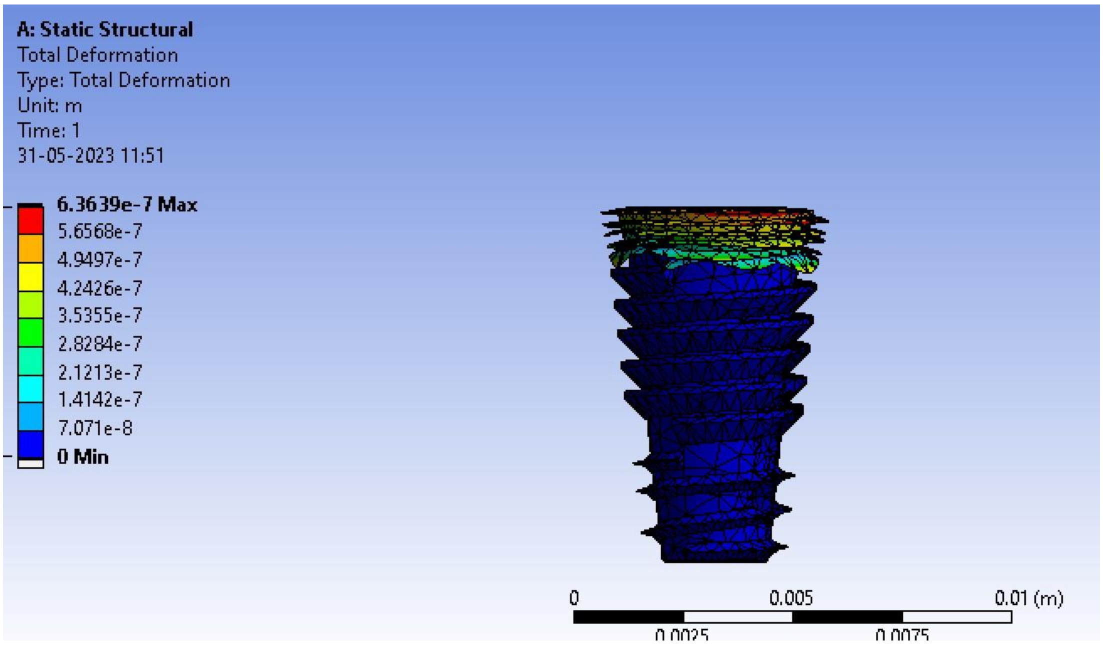

Figure 9 Total Deformation

Lowest factor of safety is 7.2

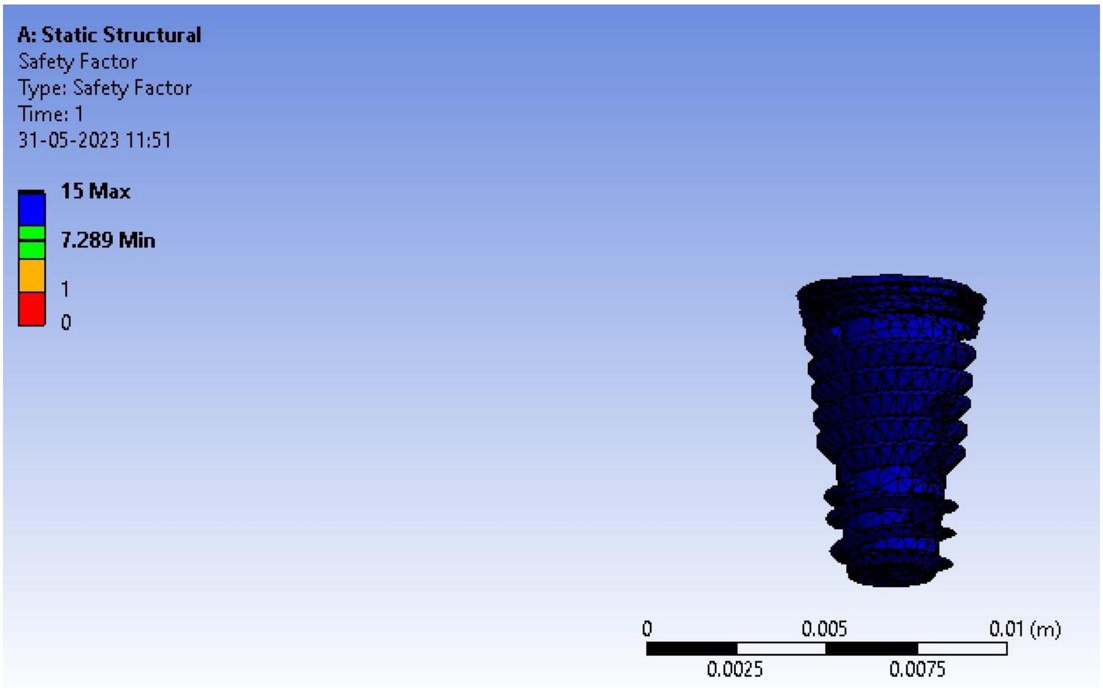

Figure 10 Factor of Safety

Maximum stress developed is 120 MPa

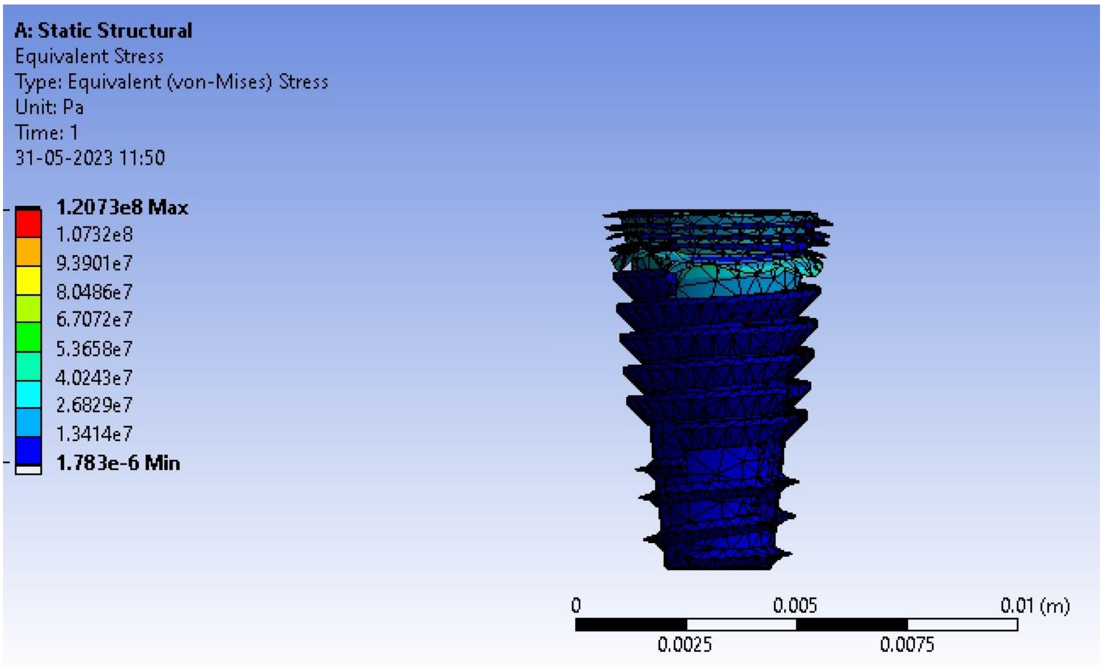

Figure 11 Von-Mises stress

CHAPTER 5 – CONCLUSION

5.1

The study arrives at a finding that the Bone-Implant Contact Area (BICA) is significantly impacted when dental implants develop greater surface roughness. Conclusions show that the dental implant's secondary stability has been enhanced as a consequence of the increased BICA. The research underlines the vitality of surface roughness as a determinant of the resilience and long-term success of dental implant operations. Clinicians may be able to boost the stability and overall functionality of dental implants by introducing surface modifications aimed at enhancing roughness, which will benefit patients' oral health and well-being.

5.2

The study suggests that incorporating a hollow cavity within the dental implant offers two notable advantages, leading to increased Bone-Implant Contact Area (BICA). Firstly, this design modification enhances the implant's osseointegrating capabilities, promoting a stronger and more stable connection with the surrounding bone tissue. Secondly, the presence of the hollow cavity allows for bone growth not only on the implant's surface but also within its internal space. This internal bone growth restricts the degree of freedom of the implant, further enhancing its stability and reducing the risk of mobility or failure. These findings highlight the potential benefits of hollow-cavity dental implants in improving long-term clinical outcomes and patient satisfaction.

5.3

The inclusion of bone growth inside the dental implant offers potential benefits for patients with osteoporosis and comorbidities. By promoting bone growth within the implant, the design reduces the overall volume of bone required to support the implant. This is particularly advantageous for patients with reduced bone density or compromised bone health, such as those with osteoporosis or comorbidities. The ability to utilize less bone volume can potentially simplify the implant placement process, minimize surgical invasiveness, and contribute to better treatment outcomes for these specific patient populations. This approach may provide a valuable alternative for individuals who have limited bone availability and can enhance their overall oral health and quality of life.

5.4

The multidirectional bone growth resulting from the introduction of a hollow cavity inside the dental implant has implications for the loading time of the implant. The study suggests that this multidirectional bone growth facilitates a more efficient and accelerated integration process. As bone growth occurs from multiple directions within the implant, it promotes a greater surface area of contact between the implant and the surrounding bone tissue. This increased contact area enhances the overall stability and strength of the implant, allowing for shorter loading times. Consequently, patients may experience reduced healing periods and earlier functional restoration, contributing to improved treatment outcomes and patient satisfaction.

5.5

Based on the conducted static structural analysis, it has been determined that the new product possesses sufficient strength to effectively handle all the applied forces. The factor of safety, calculated as 7.2, indicates a substantial margin between the maximum expected stress on the product and its actual strength. This high factor of safety suggests that the product has been designed with a significant safety buffer, ensuring its durability and reliability even under challenging conditions. The results of the analysis provide confidence in the product's ability to withstand forces and contribute to its overall performance and longevity.

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APPENDIX

Contents

Units

TABLE 1

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (A4)

Geometry

TABLE 2
Model (A4) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	C:\Users\5310\Documents\SW_dhruvsavedmodels\5x85.IGS
Type	Iges
Length Unit	Millimeters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	4.9983e-003 m
Length Y	8.5141e-003 m
Length Z	5.0849e-003 m
Properties	
Volume	8.1316e-008 m³
Mass	3.582e-004 kg
Scale Factor Value	1.
Statistics	
Bodies	5
Active Bodies	5
Nodes	23697
Elements	11946

Mesh Metric	None
Update Options	
Assign Default Material	No
Basic Geometry Options	
Solid Bodies	Yes
Surface Bodies	Yes
Line Bodies	No
Parameters	Independent
Parameter Key	ANS;DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	Yes
Compare Parts On Update	No
Analysis Type	3-D
Mixed Import Resolution	None
Import Facet Quality	Source
Clean Bodies On Import	No
Stitch Surfaces On Import	Program Tolerance
Decompose Disjoint Geometry	Yes

Enclosure and Symmetry Processing	Yes

TABLE 3
Model (A4) > Geometry > Parts

Object Name	*5x85-FreeParts*	*5x85-FreeParts[2]*	*5x85-FreeParts[3]*	*5x85-FreeParts[4]*	*5x85-FreeParts[5]*
State	Meshed				
Graphics Properties					
Visible	Yes				
Transparency	1				
Definition					
Suppressed	No				
Stiffness Behavior	Flexible				
Coordinate System	Default Coordinate System				
Reference Temperature	By Body				
Reference Temperature Value	19.85 °C				
Treatment	None				
Material					
Assignment	Ti-6Al-4V				
Nonlinear Effects	Yes				
Thermal Strain Effects	No				
Bounding Box					
Length X	3.6214e-003 m	3.8204e-003 m	4.3059e-003 m	4.8347e-003 m	4.9983e-003 m
Length Y	1.69e-003 m	1.1654e-003 m	1.8791e-003 m	2.8896e-003 m	8.5141e-003 m

Length Z	3.559e-003 m	3.802e-003 m	4.2807e-003 m	4.8053e-003 m	5.0849e-003 m
Properties					
Volume	9.9391e-010 m³	7.5899e-010 m³	3.4293e-009 m³	7.4755e-009 m³	6.8658e-008 m³
Mass	4.3782e-006 kg	3.3434e-006 kg	1.5106e-005 kg	3.293e-005 kg	3.0244e-004 kg
Centroid X	1.1911e-004 m	-2.2561e-004 m	1.0821e-004 m	-1.1121e-004 m	-2.7033e-007 m
Centroid Y	-7.7504e-003 m	-6.5033e-003 m	-4.815e-003 m	-3.0091e-003 m	-3.2541e-003 m
Centroid Z	-1.4148e-004 m	1.8844e-004 m	-1.862e-004 m	8.4672e-005 m	-4.9863e-007 m
Moment of Inertia Ip1	5.3908e-012 kg·m²	4.3153e-012 kg·m²	2.8867e-011 kg·m²	8.1032e-011 kg·m²	1.941e-009 kg·m²
Moment of Inertia Ip2	8.276e-012 kg·m²	7.3753e-012 kg·m²	4.7715e-011 kg·m²	1.2827e-010 kg·m²	4.984e-010 kg·m²
Moment of Inertia Ip3	4.2298e-012 kg·m²	3.3576e-012 kg·m²	2.2239e-011 kg·m²	7.5158e-011 kg·m²	1.92e-009 kg·m²
Statistics					
Nodes	1244	993	2223	4045	15192
Elements	435	348	897	1631	8635
Mesh Metric	None				

TABLE 4
Model (A4) > Materials

Object Name	*Materials*
State	Fully Defined
Statistics	
Materials	2
Material Assignments	0

Coordinate Systems

TABLE 5
Model (A4) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. m
Origin Y	0. m
Origin Z	0. m
Directional Vectors	
X Axis Data	[1. 0. 0.]
Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

Connections

TABLE 6
Model (A4) > Connections

Object Name	*Connections*
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

TABLE 7
Model (A4) > Connections > Contacts

Object Name	*Contacts*
State	Fully Defined
Definition	
Connection Type	Contact
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	2.7764e-005 m
Use Range	No
Face/Face	Yes
Face-Face Angle Tolerance	75. °
Face Overlap Tolerance	Off
Cylindrical Faces	Include
Face/Edge	No
Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies
Statistics	
Connections	4
Active Connections	4

TABLE 8
Model (A4) > Connections > Contacts > Contact Regions

Object Name	*Contact Region*	*Contact Region 2*	*Contact Region 3*	*Contact Region 4*
State	Fully Defined			
Scope				
Scoping Method	Geometry Selection			
Contact	1 Face			
Target	2 Faces		3 Faces	
Contact Bodies	5x85-FreeParts	5x85-FreeParts[2]	5x85-FreeParts[3]	5x85-FreeParts[4]
Target Bodies	5x85-FreeParts[5]			
Protected	No			
Definition				
Type	Bonded			
Scope Mode	Automatic			
Behavior	Program Controlled			
Trim Contact	Program Controlled			
Trim Tolerance	2.7764e-005 m			
Suppressed	No			
Advanced				
Formulation	Program Controlled			
Small Sliding	Program Controlled			
Detection Method	Program Controlled			
Penetration Tolerance	Program Controlled			
Elastic Slip Tolerance	Program Controlled			
Normal Stiffness	Program Controlled			
Update Stiffness	Program Controlled			

Pinball Region	Program Controlled
Geometric Modification	
Contact Geometry Correction	None
Target Geometry Correction	None

Mesh

TABLE 9
Model (A4) > Mesh

Object Name	*Mesh*
State	Solved
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	Default
Sizing	
Use Adaptive Sizing	Yes
Resolution	Default (2)
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Fast
Span Angle Center	Coarse
Initial Size Seed	Assembly
Bounding Box Diagonal	1.1105e-002 m
Average Surface Area	4.0727e-006 m^2

Minimum Edge Length	1.2048e-007 m
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Aggressive Mechanical
Target Quality	Default (0.050000)
Smoothing	Medium
Mesh Metric	None
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	No
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Statistics	
Nodes	23697

Elements	11946

Static Structural (A5)

TABLE 10
Model (A4) > Analysis

Object Name	*Static Structural (A5)*
State	Solved
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22. °C
Generate Input Only	No

TABLE 11
Model (A4) > Static Structural (A5) > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Off
Solver Pivot Checking	Program Controlled

Large Deflection	Off
Inertia Relief	Off
Quasi-Static Solution	Off
Rotordynamics Controls	
Coriolis Effect	Off
Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Combine Restart Files	Program Controlled
Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Program Controlled
Advanced	
Inverse Option	No
Contact Split (DMP)	Off
Output Controls	
Stress	Yes
Surface Stress	No
Back Stress	No

Strain	Yes
Contact Data	Yes
Nonlinear Data	No
Nodal Forces	No
Volume and Energy	Yes
Euler Angles	Yes
General Miscellaneous	No
Contact Miscellaneous	No
Store Results At	All Time Points
Result File Compression	Program Controlled
Analysis Data Management	
Solver Files Directory	C:\Users\5310\Documents\SW_dhruvsavedmodels\5x85analysis_files\dp0\SYS\MECH\
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Contact Summary	Program Controlled
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	mks

TABLE 12
Model (A4) > Static Structural (A5) > Loads

Object Name	*Fixed Support*	*Force*
State	Fully Defined	
Scope		

Scoping Method	Geometry Selection	
Geometry	3 Faces	1 Face
Definition		
Type	Fixed Support	Force
Suppressed	No	
Define By		Components
Applied By		Surface Effect
Coordinate System		Global Coordinate System
X Component		0. N (ramped)
Y Component		-350. N (ramped)
Z Component		0. N (ramped)

FIGURE 1
Model (A4) > Static Structural (A5) > Force

Solution (A6)

TABLE 13
Model (A4) > Static Structural (A5) > Solution

Object Name	*Solution (A6)*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done
MAPDL Elapsed Time	13. s
MAPDL Memory Used	389. MB
MAPDL Result File Size	23.938 MB
Post Processing	
Beam Section Results	No
On Demand Stress/Strain	No

TABLE 14
Model (A4) > Static Structural (A5) > Solution (A6) > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Identify Element Violations	0
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors

Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 15
Model (A4) > Static Structural (A5) > Solution (A6) > Results

Object Name	*Total Deformation*	*Equivalent Stress*
State	Solved	
Scope		
Scoping Method	Geometry Selection	
Geometry	All Bodies	
Definition		
Type	Total Deformation	Equivalent (von-Mises) Stress
By	Time	
Display Time	Last	
Calculate Time History	Yes	
Identifier		
Suppressed	No	
Results		
Minimum	0. m	1.783e-006 Pa
Maximum	6.3639e-007 m	1.2073e+008 Pa
Average	1.7651e-007 m	1.2341e+007 Pa
Minimum Occurs On	5x85-FreeParts[5]	5x85-FreeParts[3]
Maximum Occurs On	5x85-FreeParts[5]	
Minimum Value Over Time		

Minimum	0. m	8.6904e-007 Pa
Maximum	0. m	2.6691e-006 Pa
Maximum Value Over Time		
Minimum	1.2728e-007 m	2.4146e+007 Pa
Maximum	6.3639e-007 m	1.2073e+008 Pa
Information		
Time	1. s	
Load Step	1	
Substep	4	
Iteration Number	5	
Integration Point Results		
Display Option		Averaged
Average Across Bodies		No

FIGURE 2
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

TABLE 16
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

Time [s]	Minimum [m]	Maximum [m]	Average [m]
0.2	0.	1.2728e-007	3.5303e-008
0.4		2.5456e-007	7.0606e-008
0.7		4.4547e-007	1.2356e-007
1.		6.3639e-007	1.7651e-007

FIGURE 3
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Stress

TABLE 17
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Stress

Time [s]	Minimum [Pa]	Maximum [Pa]	Average [Pa]
0.2	2.1041e-006	2.4146e+007	2.4682e+006
0.4	8.6904e-007	4.8292e+007	4.9365e+006
0.7	2.6691e-006	8.4511e+007	8.6389e+006
1.	1.783e-006	1.2073e+008	1.2341e+007

TABLE 18
Model (A4) > Static Structural (A5) > Solution (A6) > Stress Safety Tools

Object Name	*Stress Tool*

State	Solved
Definition	
Theory	Max Equivalent Stress
Stress Limit Type	Tensile Yield Per Material

TABLE 19
Model (A4) > Static Structural (A5) > Solution (A6) > Stress Tool > Results

Object Name	*Safety Factor*
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Safety Factor
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No
Integration Point Results	
Display Option	Averaged
Average Across Bodies	No
Results	
Minimum	7.289
Minimum Occurs On	5x85-FreeParts[5]
Minimum Value Over Time	
Minimum	7.289

Maximum	15.
Maximum Value Over Time	
Minimum	15.
Maximum	15.
Information	
Time	1. s
Load Step	1
Substep	4
Iteration Number	5

FIGURE 4
Model (A4) > Static Structural (A5) > Solution (A6) > Stress Tool > Safety Factor

TABLE 20
Model (A4) > Static Structural (A5) > Solution (A6) > Stress Tool > Safety Factor

Time [s]	Minimum	Maximum	Average
0.2	15.	15.	15.
0.4			

0.7	10.413		14.999
1.	7.289		14.981

Material Data

Ti-6Al-4V

TABLE 21
Ti-6Al-4V > Color

Red	Green	Blue
181	168	168

TABLE 22
Ti-6Al-4V > Isotropic Elasticity

Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa	Temperature C
1.07e+011	0.323	1.0075e+011	4.0438e+010	20
1.034e+011	0.328	1.0019e+011	3.8931e+010	100
9.951e+010	0.334	9.991e+010	3.7298e+010	200
9.371e+010	0.339	9.7008e+010	3.4993e+010	300
8.55e+010	0.345	9.1935e+010	3.1784e+010	400
7.471e+010	0.351	8.3568e+010	2.765e+010	500
6.184e+010	0.357	7.2075e+010	2.2786e+010	600
4.816e+010	0.363	5.8589e+010	1.7667e+010	700
3.529e+010	0.369	4.4898e+010	1.2889e+010	800
2.45e+010	0.374	3.2407e+010	8.9156e+009	900
1.629e+010	0.38	2.2625e+010	5.9022e+009	1000
1.049e+010	0.386	1.5336e+010	3.7843e+009	1100
6.61e+009	0.392	1.0201e+010	2.3743e+009	1200
4.106e+009	0.398	6.7092e+009	1.4685e+009	1300

2.528e+009	0.403	4.3436e+009	9.0093e+008	1400
1.547e+009	0.409	2.8333e+009	5.4897e+008	1500
9.435e+008	0.415	1.85e+009	3.3339e+008	1600

TABLE 23
Ti-6Al-4V > Orthotropic Thermal Conductivity

Thermal Conductivity X direction W m^-1 C^-1	Thermal Conductivity Y direction W m^-1 C^-1	Thermal Conductivity Z direction W m^-1 C^-1	Temperature C
8.11	8.11	7.01	20
7.74	7.74	7.34	100
7.52	7.52	8.02	200
7.55	7.55	8.95	300
7.81	7.81	10.07	400
8.29	8.29	11.36	500
8.96	8.96	12.75	600
9.81	9.81	14.21	700
10.82	10.82	15.68	800
11.98	11.98	17.14	900
13.26	13.26	18.52	1000
14.65	14.65	19.78	1100
16.13	16.13	20.88	1200
17.69	17.69	21.77	1300
19.29	19.29	22.42	1400
20.93	20.93	22.76	1500

22.6	22.6	22.76	1600
28.53	28.53	28.53	1650
29.45	29.45	29.45	1700
31.28	31.28	31.28	1800
33.11	33.11	33.11	1900
34.02	34.02	34.02	1950

TABLE 24
Ti-6Al-4V > Specific Heat Constant Pressure

Specific Heat J kg^-1 C^-1	Temperature C
542.67	-253.15
552.07	-173.15
565.86	-73.15
581.58	26.85
598.82	126.85
617.21	226.85
636.34	326.85
655.84	426.85
675.3	526.85
694.35	626.85
712.58	726.85
729.62	826.85
745.06	926.85
758.52	1026.8

769.62	1126.8
777.96	1226.8
783.14	1326.8
830	1376.8
830	1426.8
830	1526.8
830	1626.8
830	1676.8

TABLE 25
Ti-6Al-4V > Isotropic Secant Coefficient of Thermal Expansion

Coefficient of Thermal Expansion C^-1	Temperature C
6.5e-006	-233.15
7.1e-006	-173.15
8.9e-006	19.85
9.7e-006	126.85
1.08e-005	326.85
1.14e-005	526.85
1.16e-005	626.86
1.16e-005	826.86
Zero-Thermal-Strain Reference Temperature C	
19.85	

TABLE 26
Ti-6Al-4V > Density

Density kg m^-3	Temperature C
4405	20
4243	1227
4189	1777
3865	1877
3730	2127
3730	2500

TABLE 27
Ti-6Al-4V > Bilinear Isotropic Hardening

Yield Strength Pa	Tangent Modulus Pa	Temperature C
1.098e+009	1.332e+009	20
8.44e+008	1.207e+009	204
6.63e+008	1.033e+009	427
5.27e+008	9.43e+008	538
6.e+007	7.08e+008	815
2.1e+007	5.96e+008	944

TABLE 28
Ti-6Al-4V > Melting Temperature

Melting Temperature C
1605

TABLE 29
Ti-6Al-4V > Tensile Yield Strength

Tensile Yield Strength Pa
8.8e+008

TABLE 30

Ti-6Al-4V > Compressive Yield Strength

Compressive Yield Strength Pa
9.7e+008

TABLE 31

Ti-6Al-4V > Tensile Ultimate Strength

Tensile Ultimate Strength Pa
9.5e+008

TABLE 32

Ti-6Al-4V > Compressive Ultimate Strength

Compressive Ultimate Strength Pa
1.15e+009