GOLF CLUB PROTOTYPING AND DESIGN FOR SPIN RATE TUNING

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by

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ABSTRACT

Golf Club Prototyping and Design for Spin Rate Tuning

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       The aim of this project was to design a golf wedge capable of increasing backspin for the amateur golfer. This was accomplished by embedding a metal lattice structure behind the clubface to allow the face to elastically deform slightly upon impact. This would increase contact time between the club and ball. The mechanism of spin generation was discussed and the relationship between contact time and spin rate was established. The design was enabled by using additive manufacturing, which allowed for the generation of a metal lattice structure. An appropriate control and prototype were designed to minimize run time and material usage due to limited machine capacity.

       Various lattice topologies were generated and analyzed with finite element analysis. Design validation build in plastic revealed that these were not feasible due to support material generation, so X topology was used instead. After printing, player testing was conducted. The prototype design underwent plastic deformation during testing, and resulted in a significantly lower spin rate than the control. The design outlined in the report is not recommended unless changes to prevent plastic deformation are made and more testing is performed. Economic justification for the production of additive manufacturing golf club designs is made in case future designs prove viable. Future work involves earlier consideration of design for manufacturability given the constraints of the selective laser melting (SLM) machine and better testing using an automated process such as a golf swing robot.

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. Introduction

This report will describe the design process for a golf wedge to improve performance for amateur golfers. Amateur golfers often struggle with generating sufficient spin to hit accurate short shots onto the green. With the development of additive manufacturing as a viable manufacturing process, embedding an internal structure within the clubhead could provide the properties necessary to increase spin by controlling face deformation.

The backspin generated by the average amateur golfer with a sand wedge is around 7,500 RPM, compared to the PGA Tour professional average of over 10,000 RPM[1]. Generation of backspin is a key aspect on a variety of shots near the green and is one of the largest advantages that professionals have over amateur golfers. By controlling face deformation and the club-ball collision, spin conditions can be optimized for wedges used by amateurs. There is an opportunity to increase backspin by 2,500 RPM.

Wedges, like all other golf clubs, are governed by regulations imposed by the United States Golf Association (USGA) and the R&A. These regulations govern club characteristics such as groove shape, clubhead dimensions, face roughness and a variety of other physical attributes. Changes to these parts of the golf club are thus limited in their impact to provide significantly better performance over existing clubs. Appendix A contains the relevant rules from the *Rules of Golf*. A creative solution is necessary to ensure that the redesigned wedge improves player performance while staying within the rules.

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[1] Extrapolated professional sand wedge spin rate based on average spin rates from TrackMan Average Tour Stats (http://blog.trackmangolf.com/trackman-average-tour-stats/). Amateur spin rate compiled from various online golf forums.

Additive manufacturing has emerged as a viable manufacturing method in recent years, with falling costs and higher-quality parts able to be produced. In relation to wedges, additive manufacturing can be used to produce internal features which have previously been impossible to manufacture using traditional methods.

The objectives of this project are as follows:

- Design and manufacture a golf wedge to increase spin rate using additive manufacturing.

- As it is unlikely that additive manufacturing will prove a cost-effective method for manufacturing wedges, propose an appropriate manufacturing process capable of mass-producing the prototype design quickly and at cost comparable to the industry.

During this project, metal additive manufacturing will be used to prototype a wedge. Prototypes will be tested against a control to determine if the goal of increasing spin rate has been achieved. Preliminary analysis of potential designs will be performed using finite element analysis. The feasibility of additive manufacturing for rapid prototyping and manufacturing of golf clubs will be evaluated. Design for manufacturability will also be considered: the cost of manufacturing the product using additive manufacturing will be estimated and an alternative low-cost manufacturing process will be recommended. This is particularly pertinent as additive manufacturing is plagued by long run-times, with a single wedge taking over 12 hours to be printed in addition to 2 hours of setup and post-processing.

The solution approach began by obtaining a computer-aided design (CAD) model of a wedge to serve as the foundation for the new design. This was accomplished by scanning a 56° Scratch Golf wedge with a NextEngine 3D scanner. At the same time, a small square sample of

wedge grooves was printed in plastic to verify the capability of additive manufacturing machines to produce the detailed features key to the golf club's performance. Once the scan was completed, the CAD file was converted to be edited in Solidworks and printed out to validate the CAD model and ensure that the wedge produced was as similar as possible to the original. Modifications were made to improve groove definition and fix some deformities at the hosel of the club.

The main concept of the design was to increase spin rate by increasing contact time between the club and ball. This was done by designing a porous metal mesh and locating it just behind the club face. Properties such as compressibility and strength of mesh structures can be predicted using finite element analysis in Autodesk Within, the same program used to design the meshes. A total of three prototype structures were initially identified and scheduled to be printed. However, after being notified of some important design constraints, it was determined that only one prototype could be built due to build issues with the geometry of all but one mesh topology.

After printing the control and prototype, player testing was conducted to determine if a significant increase in spin was observed. Statistical analysis in the form of two-way ANOVA was performed to determine if a statistical difference in mean spin rate existed between the control and prototype wedge.

Product cost analysis was done to estimate the cost to produce each wedge using additive manufacturing, and a viable manufacturing process suggested to mass-produce the prototype wedge.

This report will cover some background information regarding the theory behind backspin generation with golf clubs, existing mathematical models and simulations used to

model the club-ball impact and spin generation, finite element analysis on the club-ball impact, and previous similar applications of additive manufacturing. It will then describe the design process for the wedge and the methodology used to evaluate designs before moving on to testing and experimentation. Finally, test results will be evaluated and discussed and economic analysis of the project will be made.

II. Background

Background and literature review is divided into three sections: determining the factors influencing backspin generation in golf, mathematical models and simulations related to spin rate generation and the impact between a golf club and golf ball, and reviewing the potential benefits to golf club manufacturing brought about by the increasing efficacy and affordability of metal additive manufacturing.

FACTORS INFLUENCING BACKSPIN

The shape of grooves on the striking surface of golf clubs has been a controversial issue as of late, with the USGA introducing legislation banning the square or U-groove in 2011. Such grooves have sharp edges and a large cross-sectional area, allowing the cover of the golf ball to deform more and fill the groove (Cornish et al. 231). This allowed players to impart too much backspin on the ball when hitting out of the rough, negating the challenge of that aspect of the game. However, Cornish et al. found that while significant differences in spin rates was observed between groove types at an effective loft angle of 35°, there was no significant difference

between groove types as loft angle increased from 50° to 70°. Given that the loft of a sand wedge is typically in the range of 54°-58°, it is safe to assume that groove type plays only a small role in increasing backspin generated. Furthermore, with the USGA's regulations on grooves now outlawing U-grooves, the effect of changing groove types on backspin is likely to be limited further. In fact, the main utility of grooves is to channel water, grass and other debris away from the face upon impact. As shown in *Interim Report: Study of Spin Generation*, appreciable differences in spin rate between grooves only occurred in wet conditions.

Face roughness is another factor that influences spin rate. As Penner notes, the difference in spin rate for faces of differing roughness is more pronounced at higher loft angles (163). He references an experiment by Chou et al. in which a rougher surface imparted 67% more backspin than a smoother surface (Penner 163). Recognizing this, the USGA has imposed a limit that "sandblasting or other treatments of roughness greater than 180 micro inches are not permitted" (*Rules of Golf*). As the loft of a golf club increases, there is a tendency for the ball to slide along the face during impact as opposed to rolling. Thus, increased face roughness resists sliding and imparts a greater moment on the ball, leading to greater angular velocity and more spin. Currently, companies such as Acushnet, who make Titleist Vokey wedges, roughen the faces of their wedges using a Computer Numerically Controlled (CNC) mill (Vokey). Many companies already design wedges at the conforming limit of face roughness through processes such as micro-milling and laser milling. Cleveland Golf claims that the RTX-3 wedge, released in 2016, uses a laser milling process that roughens the face to the conforming limit (Cleveland Golf 6).

The contact time between the club face and the golf ball is a large contributor to the amount of backspin produced. "The Physics of Golf" discusses two-piece and three-piece golf

balls, and the difference between their contact time. The three-piece golf ball is softer than the two-piece ball, allowing for greater deformation of the golf ball. This increases the contact time between the club face and the golf ball, and is proven to generate more spin on the golf ball. Penner notes that Ujihashi found that the average three-piece ball is in contact with the clubface for approximately 15% longer than that of a two-piece ball, approximately 480μs compared to 420μs respectively (Penner 144-145). In a similar study, Roberts et al. found that three-piece balls were in contact with the clubface for roughly 16μs longer than two-piece balls (Penner 145). Gobush found that the deformation of the two-piece ball was 8% less than that of the three-piece ball (Penner 145). This article discusses the deformation and the coefficient of restitution (COR) of the golf ball rather than spin rate explicitly, however it claims that increased deformation leads to increased contact time and greater spin produced. While the deformation of the golf ball is not being changed, increasing elastic deformation of the wedge face should increase contact time and spin as well.

MODELS AND SIMULATIONS

To test design options before running them through the metal additive manufacturing process, finite element analysis (FEA) will be used. This analysis determines how the mesh designs created will deform during impact. This deformation can then be correlated to impact time to construct a hypothesis on the effect of increasing deformation on spin rate. As the impact between a golf club and a golf ball is difficult to model mathematically due to the multilayer multi-material construction of the golf ball, the actual change in spin rate can be measured experimentally with player testing. The use of FEA enabled rapid evaluation of different designs and mesh topologies that would most likely result in increased spin.

It is important to understand the mechanism of spin generation thoroughly to design a wedge that increases spin. Friswell and Tanaka propose models for the impact between a golf ball and a golf club, though their models focus on effects of impact on the shaft rather than on the ball. Roh's article "Analysis of Golf Ball Spin Mechanism at Impact by FEM" examines tangential force as the main driver of spin rate and the effect of ball compression on spin. In addition, two contact modes are identified: slipping and rolling. For low-angle impacts like that of a driver, the primary contact mode is rolling when the ball leaves the club. For a higher-lofted club like a wedge, the ball slips across the face during impact.

FEA simulation in Within can be used to evaluate the mesh designs. By modeling the impact force applied at impact, the stress and strain caused by the impact and the deformation profile of the club can be determined. These values and will predict whether the mesh design will be able to withstand the impact caused by the strike. After comparing these profiles, the mesh designs with the greatest deformation will be selected, as these mesh designs have the most potential to impart greater spin to the ball.

METAL ADDITIVE MANUFACTURING

The advancement of additive manufacturing (AM) technology has resulted in increased applications in the aerospace, biomedical and automotive fields. This project aims to extend applications of additive manufacturing—specifically, metal additive manufacturing—to sporting equipment.

Some benefits of AM are greater ability to rapid prototype and more efficient use of materials (Frazier 1925). In addition, AM can manufacture intricate internal structures that

traditional conventional processes are unable to produce. This is the main reason AM was selected.

There are, however, limitations to structures that can be manufactured with AM, specifically with selective laser melting (SLM) that is intended to be used for this project. Some important considerations that need to be made are part geometry and orientation. For example, any struts or structures at less than 45° from horizontal need to have support structures built (Thomas 160). Unfortunately, these were not considered until the designs were completed and ready to be built. Thus, they did not impact the initial design and a redesign was needed to meet these requirements.

Ray et al. have conducted research into AM technology to create regions of low density within a golf club, allowing weight to be redistributed and the center of gravity (COG) relocated (665). They propose creating a porous metal mesh, the density of which is carefully controlled, and inserting this into an iron or driver. This would allow movement of the COG low and to the back of the club and increase the moment of inertia (MOI) of the clubhead by moving weight to the perimeter of the club (658). Moving the COG changes the trajectory and spin imparted on the ball, while increasing MOI produces straighter shots on off-center hits (658). The main metal AM feature in the design is a printed metal foam with carefully controlled porosity. Using ANSYS LS-DYNA software to simulate the interaction between club and ball, it was found that increased porosity led to lower values of coefficient of restitution (COR) and enabled COG to be lowered. This is most beneficial for short irons and wedges, with which the desired flight is high and with a high spin rate. Increasing porosity also resulted in an increased contact time, which as previously discussed would result in increased backspin.

Building on this research, which included only software simulation and analysis and was a general study of the benefits additive manufacturing could bring to golf club design, the aim of this project is to build a physical prototype wedge which results in more backspin being generated. A low-density mesh will be important in the design as it elastically deforms to increase contact time with the golf ball, thereby increasing spin rate.

Next, the design procedure for developing the new wedge design and the theory behind the design will be discussed.

III. Design

As previously mentioned, golf club characteristics and performance are strictly regulated by golf's governing bodies. Thus, the solution approach taken to tackle this problem must be innovative. Instead of focusing on factors such as grooves or face roughness, which would require minimal design, the approach was to make use of new technology to radically redesign the wedge.

THEORY

Spin imparted on the golf ball is affected by contact time, which usually varies based on the compression rating and construction of the ball. Penner states in his article "The Physics of Golf" that the average contact time for a three-piece ball is "15% greater than the contact time for two-piece balls" (144). This is correlated to a consistently higher spin rate for three-piece balls compared to two-piece balls over a variety of impact angles (Penner 148).

Besides changing ball characteristics, contact time can also be lengthened by increasing elastic deformation of the club face on impact. Hocknell proposes that the contact time between a golf club head and a golf ball can be estimated by Equation 1:

$$\tau = 4.53 \left[\frac{(\delta_A + \delta_B) m_B}{\sqrt{R_B v_0}} \right]^{2/5} \tag{1}$$

Where,

$$\delta_A = \frac{1 - v_A^2}{\pi E_A} \quad \text{and} \quad \delta_B = \frac{1 - v_B^2}{\pi E_B} \tag{2}$$

Increased deformation affects the effective Young's modulus (E) and Poisson's ratio (v) of the club. Increased deformation under the same force means that strain would increase with stress remaining the same. This would lead to a decrease in the effective Young's modulus of a unit volume of mesh. Poisson's ratio could also be affected depending on deformation in the transverse directions.

This equation is based on Hertz theory regarding the oblique impact of elastic spheres. The theory is limited for this application as it assumes the impact area is small compared to the dimensions of the colliding bodies and duration of impact is long compared to the period of the lowest mode of vibration of the bodies (Roberts et al. 202). Despite this, it does provide a close approximation: Hocknell estimated an error of 7% compared to an experimentally-obtained contact time (18). By adding a metal mesh structure, the face of a wedge can be made to deform upon striking the ball, increasing contact time in that manner.

The effect of increasing contact time on spin has been examined by Ray, who notes that increasing the porosity of the clubhead can increase the contact time, leading to an increase in

spin. The article is a theoretical look at the possibility and impact of using additive

manufacturing methods to produce a porous metal interior for golf clubs. Contact time is graphed

as a function of porosity level (Ray 667). For this project, the metric used is not porosity but

deformation. This is arguably a better measure as the mesh structure can be tuned to achieve

maximum deformation without compromising on material density and hence the structural

integrity of the club.

The mechanism of imparting spin at high angles—over 45°—is also explained by Penner

with reference to work by Johnson and Lieberman. At high impact angles, the shell of the ball is

in sliding contact with the club face during impact as opposed to rolling contact. This results in

less spin being generated at higher impact angles: 116 revolutions per second at 55° compared to

127 revolutions per second at 45° (Penner 148). Increasing contact time would allow more spin

to be generated as the tangential frictional force will be imparted over a longer duration.

Additionally, increased contact time could possibly result in rolling contact.

The impact of a golf ball is inherently difficult to model because of the multilayer, multi-

material construction of modern-day balls, and it is unlikely that a perfectly reliable

mathematical model exists to calculate contact time or spin rate purely theoretically. Thus,

experimentation will play a crucial role in determining if spin rate does increase due to the new

wedge design.

MESH DESIGN

The initial intent was to print the control wedge and prototype wedges as a single piece.

However, this was deemed risky as the Selective Laser Melting (SLM) machine used to

manufacture the parts experienced issues with lengthy builds. Hence, it was necessary to explore different ways to print a control and prototype. The method chosen was to print a solid wedge body with a cavity and several inserts that would be screwed into the body. This would require only one wedge body to be printed and would reduce the print time and material cost for prototypes as only inserts would need to be printed. In addition, only one hosel drilling and shaft attachment operation would need to be performed.

Concept Exploration:

As internal mesh designs are limited by the geometry of the wedge, three mesh insert size and location concepts were explored.

Concept 1:

Uniform-depth mesh across the entire face. Due to limits in the thickness of the top half of the wedge and the need for face thickness of at least 1mm, this would result in a mesh thickness of about 2mm across the entire face.

Concept 2:

Rectangular cross section mesh across the impact region. This would allow a much thicker mesh of up to 15mm, but the face area that would experience the effect of the mesh is greatly limited due to the profile of the golf club.

Concept 3:

Trapezoidal cross section mesh. This would allow for a maximum mesh thickness of around 10mm, tapering off towards the top and bottom of the impact zone, and a larger area of effect of the mesh compared to concept 2.

Evaluation Criteria:

The following considerations were made when selecting the concept to be used:

1. Consistency of mesh effect across impact area (mesh surface area).

    a. This is required because it is impossible to hit the exact same spot every time during player testing. Hence, it is important for a consistent mesh effect to be present in the region where impact is most likely to occur.

2. Effect of mesh on face deformation (mesh thickness).

    a. The mesh will deform by a fixed percentage given the same impact force, therefore a thicker mesh would result in larger deformation. To significantly increase spin rate, maximum deformation is desired. The mesh should be as thick as possible to accomplish this.

Concept Selection:

To select a concept, Multi-Criteria Decision Analysis (MCDA) was performed. Weights for each criterion were calculated by summing the surface area or thickness for each concept and taking the reciprocal.

	Surface Area (mm^2)	Thickness (mm)	
Weight	1/4050	1/27	
Concept 1	2300	2	0.642
Concept 2	400	15	0.654
Concept 3	1350	10	0.704

Table 1: Mesh Size and Location MCDA

Based on the MCDA, Concept 3 was selected. In addition to designing the mesh shape, a method to secure the inserts needed to be created. This was done by adding tabs on the left and right of the insert. Holes for a 3mm diameter screw were added to the tabs. The back of the wedge body featured mating 3mm holes and a hex counterbore so that a nut could be inserted to secure the screw. The final design of the wedge body and insert is shown in Figure 1 below.
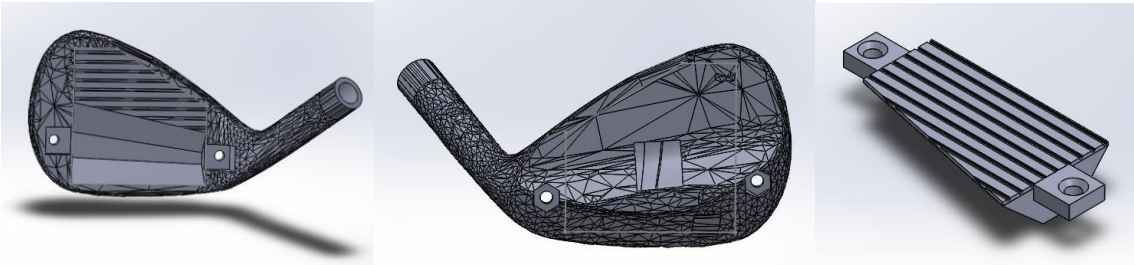
Figure 1: Wedge Body and Insert Design

MESH TOPOLOGY

Autodesk Within was the program used extensively during this project to generate mesh designs and simulate stresses and deformation. It is packaged with 20 topologies and allows for rapid iteration and evaluation of designs. Once the desired part has been imported, mesh and skin conditions are selected and the component is generated. This enables the user to evaluate the part visually and provides information such as the volume reduction coefficient, which refers to the proportion of the initial volume that remains solid after implementing the lattice structure.

14

Simulation is also simple to perform: once load conditions are defined globally the part can be simulated for each different mesh design at the click of a button. The forces need not be redefined unless a different part is used.

Preliminary mesh topology selection was performed by simulating each of the 20 topologies with a 5x5x5mm unit size and 0.3mm beam thickness. The maximum deformation, load buckling safety factor (LBSF) and maximum lattice stress was recorded for each topology. The results can be found in Appendix B. Mesh loading conditions are calculated in Appendix C. An example of the simulation output is shown in Figures 2 and 3 below.
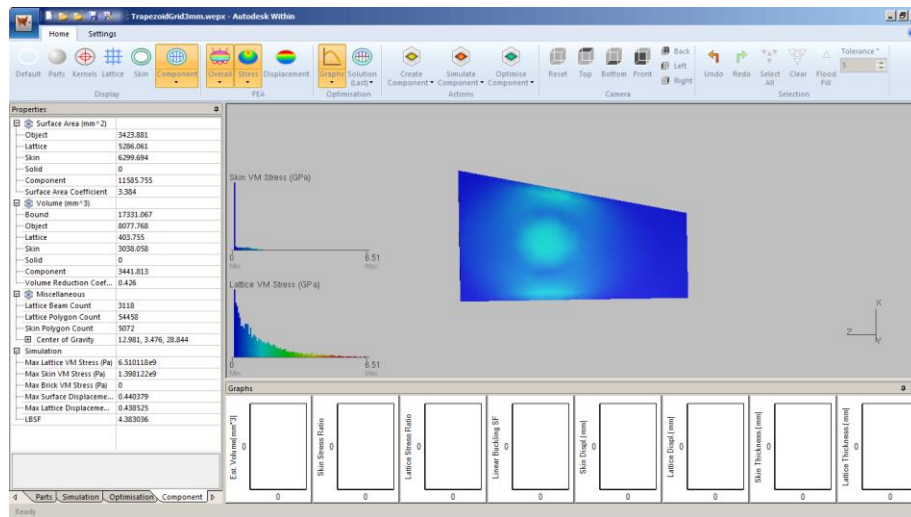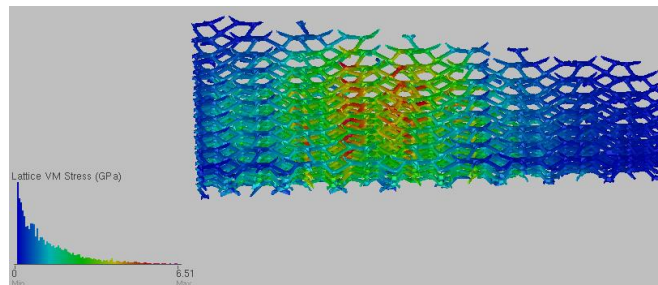

Figure 2: Stress Analysis Skin View

Figure 3: Stress Analysis Lattice View

Mesh Topology Shortlist:

From the preliminary simulation results, Crush and Dark Horse topologies were identified as undergoing the most deformation while maintaining an acceptable LBSF. To determine if the unit size and beam thickness could be further optimized, iterations of these were simulated. The results are shown in Table 2 below.

Mesh Topology	Unit Size (mm)	Beam Thickness (mm)	Max Displacement (mm)	LBSF	Max Lattice Stress (GPa)
Dark Horse	3x3x3	0.3	0.440	4.4	6.5
Dark Horse	5x5x5	0.3	0.701	1.5	11.4
Dark Horse	5x5x5	0.5	0.406	4.8	5.7
Dark Horse	6x6x6	0.5	0.472	3.0	7.0
Dark Horse	8x8x8	0.5	0.610	2.1	9.7
Crush	5x5x5	0.3	0.776	9.3	6.8
Crush	5x5x5	0.4	0.612	12.3	6.3
Crush	5x5x5	0.5	0.431	18.5	5.0
Crush	6x6x6	0.5	0.425	11.1	7.1
Crush	7.5x7.5.x7.5	0.5	0.709	10.5	5.5
Crush	10x10x10	0.5	0.532	4.2	13.0

Table 2: Shortlisted Topology Simulation

From these designs, the lattice structures highlighted in yellow were selected as they were predicted to experience the most deformation and had a high LBSF.

IV. Methodology

CAD MODEL ACQUISITION

To design a prototype wedge, a CAD model of a wedge was required. Since most companies use roughly the same generic wedge design, a wedge model was obtained by

performing a digital scan of an existing wedge made by Scratch Golf. This scan was performed with a NextEngine 3D digital scanner. To get this scan into an editable solid body model in Solidworks, modifications needed to be made within the NextEngine program, and then the file size was reduced in Netfabb.

As shown in Figure 4 below, the wedge had to be oriented in the middle of the circular plate. Next the scanner took 16 partial scans, changing the orientation by an angle of 22.5° for each scan. These 16 scans were then merged together to create one accurate 360° CAD representation of the wedge.

The quality of the first scan was poor, as the scanner was unable to identify certain regions of the wedge, so many of these regions were missing from the model. This issue was due to the shiny finish of the wedge and light reflecting off the wedge during the scan. To resolve this issue the wedge was coated in a matte white spray powder to eliminate any reflection during the scan. The second scan was of better quality, but still required minor repairs to clean it up. These repairs included smoothing surfaces which were touching supports during the scan and filling small holes.

To import the solid body to Solidworks, the file size had to be severely reduced. This was accomplished by transferring the scan to Netfabb and reducing the number of triangles in the model from 1.4 million to just over 6,000. This reduction allowed the CAD model to be imported to Solidworks, where the appropriate changes could be made.
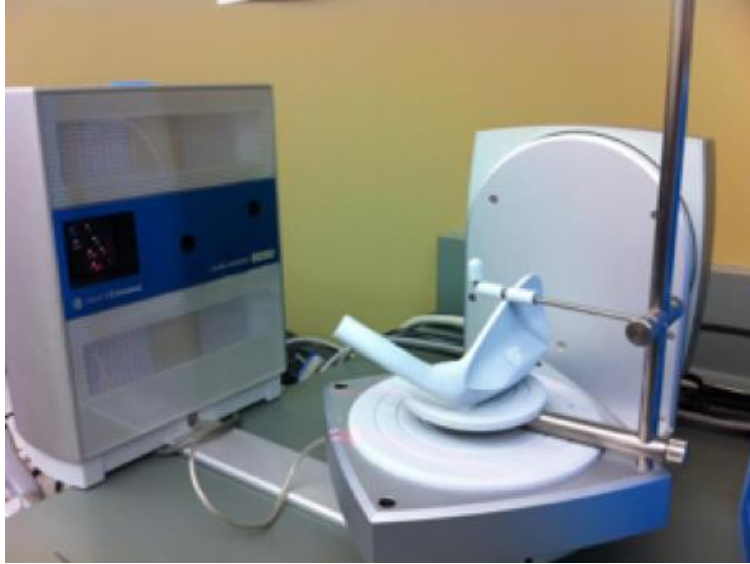
Figure 4: NextEngine 3D Digital Scanner Setup

CAD MODEL VALIDATION

Prior to building the wedge designs with the SLM machine, it was necessary to ensure that the additive manufacturing techniques were capable of producing the wedge and the precise grooves on the face of the wedge. To test this, a small sample of grooves was created and printed in plastic (see Figure 5 below). The quality and precision of the printed groove sample was very similar to grooves on an actual club.

Figure 5: Sample of 3D Printed Grooves

Once the CAD wedge model had been acquired, a plastic model was printed to ensure that there were no issues with the model size or quality. This plastic model can be seen in Figure 6 below. It was of good quality, but lacked the groove structure and quality needed.

Figure 6: 3D Printed Model of Scanned Wedge

To improve the groove definition, the grooves of the scanned model were removed and replaced with grooves which were modeled in Solidworks based on *Interim Report: Study of Spin Generation* published jointly by the R&A and the USGA. The groove profile used is shown in Figure 7. To ensure compatibility and ease of attachment to a shaft, the top of the hosel, which displayed some irregularities, was repaired as well. Initially the hosel was a solid cylinder which means a hole would need to be drilled in the hosel once the wedge was built, so a hole was added to the hosel of the Solidworks model to reduce post processing.
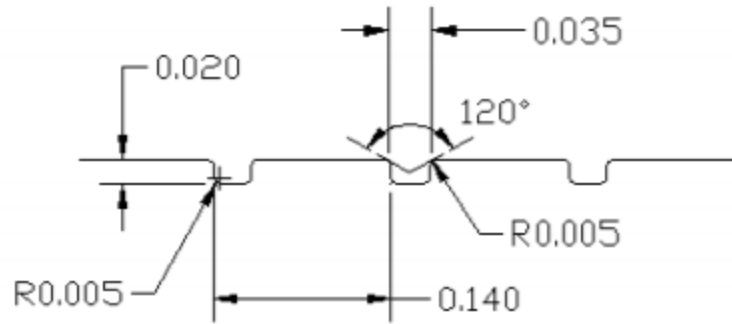
Figure 7: Groove Profile

DESIGN VALIDATION

Before building the final designs with the SLM machine, the final wedge, control insert, and mesh insert were all printed in plastic to ensure that the components would fit together and identify if any adjustments needed to be made (Figs 8, 9, 10, 11). This included the insert fitting in the wedge cavity, the bolts through the insert tabs, the nuts in the countersinks, and the shaft in the hosel. All parts fit together after some sanding, though the screws and nuts did not fit into their holes easily. Appropriate adjustments were made to the models of the various parts to add clearance.

Design validation is important to ensure that the designs function as intended. When the mesh insert was cut open to reveal the inner lattice structure, it was discovered that supports had been built in the cavity along with the lattice, rendering the cavity almost completely filled with material. As a result, the design was clarified with David Otsu, lab technician for the SLM machine, and he verified that the lattice structures would have to be built with supports. With this in mind, a design change was made. Mesh topology was changed to X, the only topology that fit the design requirements. Instead of printing three prototypes, only one prototype could be printed due to design and space restrictions. All parts required were printed in a single build.
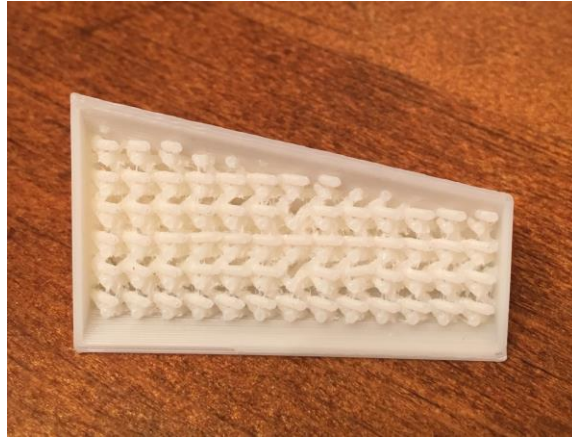
Figure 8: Plastic Model of Crush Lattice Topology
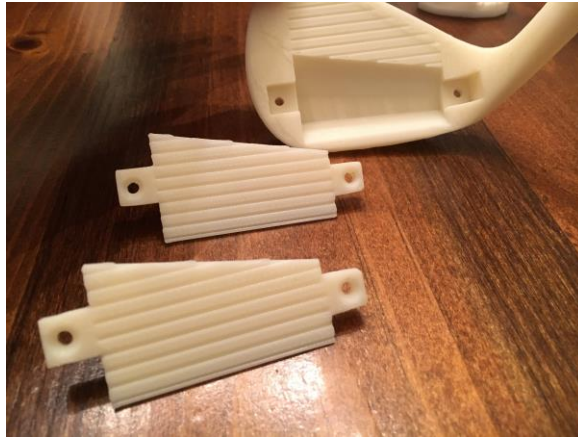
Figure 9: Plastic Models of Final Wedge and Inserts

Figure 10: Plastic Assembly of Final Wedge and Insert

Figure 11: Rear View of Hex Counterbored Bolts

The insert that was designed to be screwed into the wedge body consists of four components: the trapezoid mesh, a face with grooves and two tabs with holes. As the face and tabs were created with Solidworks and the mesh was modified in Within, a method to mate the components was needed. The mesh could not be imported into Solidworks as the model had too many surfaces for the program to handle.

To overcome this problem, Netfabb was used as an intermediate program to merge the components. The grooves and tabs were assembled in Solidworks and exported as an STL file. For the meshes, a 1mm skin was specified on the bottom and side surfaces of the mesh, leaving the top of the trapezoid open so that the grooves could be assembled on top. This was also exported as an STL file. The two mating parts are shown in Figure 12 below.
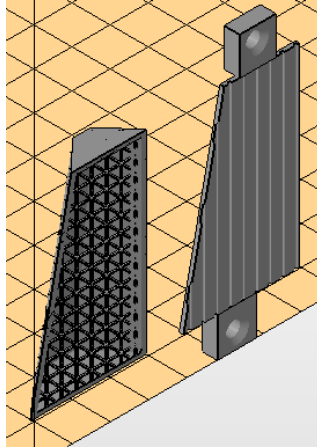
Figure 12: Insert Assembly in Netfabb

This method allowed solid regions to be combined with the lattice structure generated in Within. While the solution developed seems trivial, attempting to combine such features in either Solidworks or Within would have been near-impossible. Netfabb is primarily used for preparing additive manufacturing builds and design optimization as opposed to traditional CAD tasks, so the discovery that it has the capability to merge parts as described was an important, if unintended, finding of the project.

PLAYER TESTING

Once the wedge build was completed by the SLM machine, some post processing had to be done before testing could be conducted (see finished build with plate in Figure 13). Steel supports on the back side of the wedge and inside the hex counterbores had to be removed by crushing them in a vise and chiseling the remains away, followed by grinding (Figure 14). As the surface finish on the striking faces was rough, they were sanded down. The inside of the hosel also had to be enlarged by boring. Once the golf shaft would easily slide into the hosel, epoxy was used to secure the shaft inside of the hosel. As the shaft already had a grip on it, the wedge was ready to test with the control and the meshed inserts.
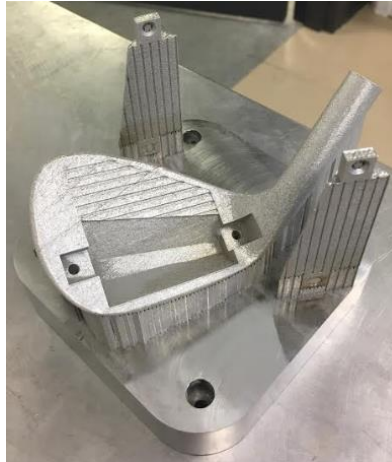
Figure 13: Completed Build

Figure 14: Post-processed Parts

Player testing was conducted by hitting balls off a mat to control the striking conditions as much as possible. In addition, brand new Taylormade Tour Preferred X balls were used to reduce variability that could occur because of inconsistent balls. A layer of foam was placed between the inserts and wedge body for vibration dampening.

Data was collected with a Flightscope, which uses radar to detect the club and ball during a golf shot. While information such as club speed, ball speed, attack angle and other metrics were collected, only spin rate was used for statistical analysis.

V. Results

EFFECT OF DEFORMATION ON CONTACT TIME

Based on Hocknell's contact time equation (Equation 1) and the mesh properties

calculated in Appendix D, contact times for the stainless steel insert and each of the prototypes

initially intended to be produced, as well as the final prototype, are shown in Table 3 below.

These are close to the literature value of 450μs (Roberts 201).

Insert	Contact Time (μs)	% Increase from Control
Control	429.3	
Crush 5x5x5mm unit size 0.3mm beam thickness	431.2	0.45
Crush 7.5x7.5x7.5mm unit size 0.5mm beam thickness	431.3	0.45
Dark Horse 3x3x3mm unit size 0.3mm beam thickness	430.8	0.35
X 4x4x4mm unit size 0.3mm beam thickness	431.1	0.42

Table 3: Contact Time Calculation

This minimal increase in contact time can be traced back to Equation 1. The variable that

changes between inserts is δ_A. In the contact time equation, this is added to δ_B, obtained from the

ball. The order of magnitude of δ_B is three times higher than that of δ_A, hence even though

Young's modulus decreased by an order of magnitude from the control to the prototypes, the

25

theoretical effect on contact time was minimal. Player testing is necessary to determine if a significant increase in spin can be obtained.

PLAYER TESTING RESULTS AND ANALYSIS

Two players performed testing with the control and prototype, hitting 17 balls[2] with each wedge. The spin rate summary statistics for each player and wedge are shown in Table 4 below.

Player	Wedge	Mean spin rate (rpm)	Standard deviation (rpm)
A	Control	9600	668
A	Prototype	8974	364
B	Control	10493	602
B	Prototype	10388	575

Table 4: Player Testing Summary Statistics

I-MR control charts were used to determine if there were any outlying data points that needed to be removed. No outliers were observed. These charts can be found in Appendix E.

During testing, plastic deformation of the prototype insert was observed after one shot was hit. The insert continued to deform as testing proceeded, but did not buckle. Figure 15 shows the deformation of the insert at the end of testing.

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[2] Sample size selected based on industry testing standard of 15-20 balls for player testing.

Figure 15: Prototype Insert Plastic Deformation

Two-way ANOVA was conducted to determine if the prototype wedge had a significant effect on spin rate at the 95% confidence level (see Appendix F). It was found that the spin rate was significantly lower with the prototype than with the control insert, with a p-value of 0.010. This is contrary to the initial hypothesis that the prototype insert would cause an increase in contact time and increase spin rate. One possible reason for this is that the plastic deformation of the insert did not allow the grooves to have as much of an effect with the prototype than with the control.

As mentioned earlier, the insert faces were sanded down to improve surface finish. A by-product of this was that the rounded groove edges were also removed, leaving sharp groove edges. Though this was consistent across both inserts, it is possible that the sharp edges had a greater effect with the control insert than with the prototype. As the prototype underwent plastic deformation, the golf ball would deform less in return, leading to shallower interfacing with the grooves and a smaller contact area. A visible difference was observed between the golf ball covers after hitting with the control insert versus the prototype insert, with more cutting and damage to the surface noted with the control insert. While literature suggests that grooves should have a minimal effect in dry conditions, the grooves considered in that study are not sharp

grooves. Hence, it is reasonable to suggest that this could be the reason for the difference in spin between inserts.

VI. Conclusion

A significantly lower spin rate was observed with the prototype insert. However, other factors other than the metal lattice structure—such as plastic deformation of the clubface—could have influenced the data. Thus, no conclusion can be drawn as to whether a metal lattice structure increases contact time significantly enough to result in an increase in backspin generated. It is not recommended that this design should be pursued at this time. Further testing is recommended with greater face thickness, greater beam thickness or decreased unit size to avoid plastic deformation.

As a rapid prototyping technique, additive manufacturing can produce prototypes quicker than traditional techniques as no tooling, fixtures or molds need to be designed. Significant post-processing is needed to obtain a surface finish comparable to traditional processes. Considering golf manufacturers have already invested in special tooling and fixtures dedicated to producing golf clubs, the best application of additive manufacturing for rapid prototyping would be for radical changes in shape or for internal features.

The economic feasibility of mass-producing a golf club by additive manufacturing is tenuous at best. Besides the high machine cost, the cycle time to produce one unit is high at around 12 hours or more. Assuming spin rate can be increased with an adjustment to the

prototype design or a similar design with additive manufacturing can be proven to increase spin rate or otherwise produce desirable effects in the future, the economic viability of such a venture is outlined in the section below.

To determine if the design would be a viable business venture, a five-year economic analysis was performed. Manufacturing industry knowledge from technical advisor Dr. Xuan Wang was used to determine the labor costs. Another cost factor necessary to perform the economic analysis was material costs for both processes. The final and likely most important factor for the five-year economic analysis is the capital cost invested to purchase the equipment necessary to create the wedge design. Each of these factors will be discussed in more detail in the following sections. The cost and revenue for the SLM process was estimated and compared to cost and revenue that could be generated with the same number of man-hours using traditional manufacturing processes.

Labor Cost:

Labor required for production with the SLM machine is two hours per build for setup and post-processing. Assuming each build takes 10 hours and there are two shifts, this results in four hours of total labor time per day, split between two operators. With limited production quantity of three wedges per build or six per day and labor rate of $75 per hour, the labor cost for 3D printing the entire wedge is $50 per wedge.

Assuming this occurs in a facility producing other items, the opportunity cost for the SLM process is 4 man-hours. Assuming labor rate of $60 per hour and that 16 wedges can be produced

in 4 man-hours, the labor cost per wedge for the traditional manufacturing process is $15. The extreme discrepancy is caused by the limitations in production quantity of the SLM process.

Material Cost:

The cost of materials for the SLM machine was provided by Dr. Wang. This cost was broken up into two major parts: the $300 cost of the plate that the printer uses as its base and the cost of the powder which can vary from about $2 per pound to $150 per pound based on quantity and quality. The cost for the plate was reduced on a per run basis because it can be used anywhere between 30 and 50 times if machined properly after each run. Based on using 30 runs per plate and using a fairly low powder cost of about $3 per wedge the material cost for this process is $6.33 per wedge. The raw material cost for traditional manufacturing was found to be approximately $1.50 per wedge. This is likely an overestimation but will be sufficient for basic cost analysis. SLM process material cost is higher than traditional process material cost but could be lowered with higher production quantities.

Equipment Cost:

For the five-year economic analysis of the wedge production process, the factor that has the largest impact on the comparison is the capital equipment costs. For the 3D printing process, the SLM machine must be purchased at $500,000. This is compared to the $100,000 or so that it would cost for the CNC mill used in the current process. For this analysis, however, the assumption was made that this process would be attempted by a company who already produces wedges, and thus spends no money on new equipment.

The economic analysis performed on the two processes for wedge production showed that the SLM process should not be pursued even if a viable design is made in the future. Even with the ability to price the wedge at twice its counterpart ($200 rather than $100), the analysis shows that over five years, the SLM process will net approximately $460,000 and the current process will net approximately $1.5 million with the same number of operators. Based on this analysis (shown in Appendix G) it is not recommended that companies pursue this process as a business endeavor.

ALTERNATIVE MANUFACTURING PROCESS

As the SLM process is not economically viable in compared to the current wedge manufacturing process, an alternative manufacturing process must be designed for production to be economically feasible. The new process must allow for a similar mesh-like structure while increasing the production rate to offset the SLM capital cost. The design that seems most reasonable is to cast or forge the wedge similar to the current process. The casting will, however, include a slot in the toe of the club that will allow for a printed mesh structure to be inserted into the wedge behind the clubface. The slot will then be either filled with a low-density resin to hold the mesh in place or plugged with an insert. This process will allow for the meshes to be printed per build and with a shorter build time, increasing yield significantly. Though this option could be pursued, it has not reached an official design phase and is merely an idea that could be further investigated.

For this alternative manufacturing process, another five-year cost analysis was performed to determine the economic plausibility of the design. For this new process, there was an assumed capital equipment cost of $520,000 for the SLM machine and new molds and fixtures for the

other processes. The labor cost was determined to be $22.50 per wedge which is based on the labor to run the SLM machine at higher quantities than the first SLM design. The material cost was cut down significantly to $2 per wedge as production has increased from 6 per day to 16 per day, spreading the cost of the build plate over more parts. With each of these individual costs resulting in a $24.50 per wedge cost as well as the selling price of each wedge being increased to $200 as in the other design, the five-year net profit for this process is approximately $2.6 million. With this process netting an approximate $1 million more than the current process, it would be reasonable to pursue this as a possible business endeavor for a wedge company.

ADDITIVE MANUFACTURING DESIGN RULES

In traditional manufacturing processes such as casting or machining, it is important to consider manufacturability when designing a part. One of the pitfalls that befell this project is that the rules for designing for additive manufacturing—and for using selective laser melting in particular—were not known or considered during the design process. Hence, the design work and simulation done was rendered useless when it was discovered that only one topology was feasible to print without supports. This was an especially important consideration as it would have been near-impossible to remove supports from within the lattice structure.

It was discovered towards the end of the project that there has been some research on appropriate design rules for selective laser melting. Thomas points out that while designing for additive manufacturing allows for "more geometrical freedom than with traditional processes... many process limitations apply and need to be considered" (155). Some process limitations that are particularly applicable to this project are listed below (Thomas 160-82):

1. Surfaces less than 45° from the substrate plate require support structures to avoid build failure.

2. Surface finish is best on vertically-oriented surfaces, and progressively degrades until it improves at 0° upward-facing.

3. Material allowances should be added as follows: 0.3mm to 0.7mm for up-facing surfaces and 0.8mm on down-facing surfaces. This allows material to be removed for good surface finish and dense surfaces. No allowance is needed for side wall surfaces.

4. Minimum size between features is 0.3mm.

5. Minimum wall thickness is 0.4mm (it is not clear if this applies to struts in lattices).

6. It is not possible to build 0° overhangs; chamfers or fillets should be added if possible.

7. The smallest hole possible to be built parallel to the substrate plate is 0.7mm diameter.

8. Upright holes can only be built without supports from 1mm to 7mm diameter, and the upper layers will tend to sag.

9. The general tolerance of round holes is ± 0.5mm.

Additional rules outline limits for chamfers and fillets, designing self-supporting holes with peaks and allowances to drill and tap holes. In future projects, it would be helpful to keep these rules in mind when designing parts to be manufactured via selective laser melting.

FUTURE WORK

Given more time to work on this project, the prototype design could be tweaked by increasing face thickness, increasing beam thickness or reducing unit size. This would produce a stronger lattice structure that does not plastically deform. It would also be beneficial to design another mesh manually, accounting for the design rules for selective laser melting. Autodesk

Within allows users to generate their own lattice structure; it is possible that this could be used to propose several different structures that increase deformation while still being feasible to manufacture.

Given more resources such as access to a golf robot, more precise testing could be performed. Using a robot would remove many more factors that could confound data such as swing speed and contact point. This would reduce the variability within a sample greatly, allowing a smaller difference in spin rate to be detected as significant.

If it is found that a wedge of this design can provide a significant increase in spin rate, further research would need to be conducted to determine economic feasibility and a viable manufacturing process. The alternative process proposed in this report is theoretical; the tooling and manufacturing processes mentioned would need to be formally designed to determine if the process is in fact feasible.

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APPENDICES

APPENDIX A: USGA RULES ON CLUBS

Guide to the Rules on Clubs and Balls

5. Club Face

a. General

Appendix II, 5a states that:

> The face of the club must be hard and rigid and must not impart significantly more or less spin to the ball than a standard steel face (some exceptions may be made for putters). Except for such markings listed below, the club face must be smooth and must not have any degree of concavity.

If claims of excessive spin are made by the manufacturer, or if there is strong supporting evidence of excessive spin, then the club could be deemed to be non-conforming.

b. Impact Area Roughness and Material

Appendix II, 5b states that:

> Except for markings specified in the following paragraphs, the surface roughness within the area where impact is intended (the "impact area") must not exceed that of decorative sandblasting, or of fine milling. The whole of the impact area must be of the same material (exceptions may be made for clubheads made of wood).

(i) Definition of 'Impact Area'

Irons

The impact area for irons is that part of the club where a face treatment has been applied (e.g., grooves, sandblasting, etc.) or the central strip down the middle of the club face having a width of 1.68 inches (42.67 mm), whichever is greater.

Note: Grooves and/or punch marks traditionally used to mark the impact area, or any groove which encroaches into the heel or toe portions of the impact area by less than 0.25 inches (6.35 mm) do not have to meet the specifications detailed in Supplement C. However, such markings must not be designed to unduly influence, or have the effect of unduly influencing, the movement of the ball.

For clubs with inserts in the face, the boundary of the impact area is defined by the boundary of the insert, as long as any markings outside the boundary do not encroach the

impact area by more than 0.25 inches (6.35 mm) and/or are not designed to influence the movement of the ball. Moreover, the insert itself must extend to at least 0.84 inches (21.34 mm) on either side of the center line of the face and to within at least 0.2 inches (5.08 mm) of the top line and leading edge of the face.

Please note that the above definitions of impact area only apply to new models of clubs manufactured on or after January 1, 2010. For clubs available prior to January 1, 2010, please refer to Supplement A (page 52 of this Guide).

(ii) Impact Area Roughness

When dealing with the surface roughness of a club face (not including putters, see Design of Clubs, Section 5f), the claims made by the manufacturer must be taken into account - especially if there is a claim that the roughness of the face influences the movement of the ball. In the absence of such claims, the ruling would be made purely on the amount of roughness in the impact area. *Sandblasting or other treatments of roughness greater than 180 micro inches are not permitted. In addition, for milling, the crest to trough depth must not exceed 0.001 inches (0.025 mm). A reasonable tolerance is allowed for both of these measurements.* Non-conforming sandblasting or milling usually feels rough to the touch.

(iii) Impact Area Material

The requirement that the whole of the "impact area" must be of the same material does not apply to clubs made of wood or putters (see Design of Clubs, Section 5f). The reason why it does not apply to wooden headed clubs is to allow the continued use of wooden clubs which have plastic inserts and brass screws in the center of the face. This design was commonly used in persimmon woods, which may still be in use. However, a club face or insert made of a composite material would be considered to be of a single material, and therefore would not be contrary to this rule.

Metal wood club faces which have inserts of different material, not trapezoidal in shape, may be permitted if the height of the insert meets the definition of "impact area" and the width of the insert is the same as the height in at least one point. However, in order to preserve the intent of the "same material" Rule, clubs which have unusually shaped inserts of different material (i.e., other than circular, oval, square or rectangular) are not normally permitted.

If an insert of different material is permitted under the above guideline, the insert would be considered the "impact area" for that club. Therefore, any markings outside that area need not conform to the specifications provided in Appendix II, 5c. However, such markings must not be designed to unduly influence the movement of the ball.

c. Impact Area Markings

Appendix II, 5c provides the specifications for impact area grooves and punch marks.
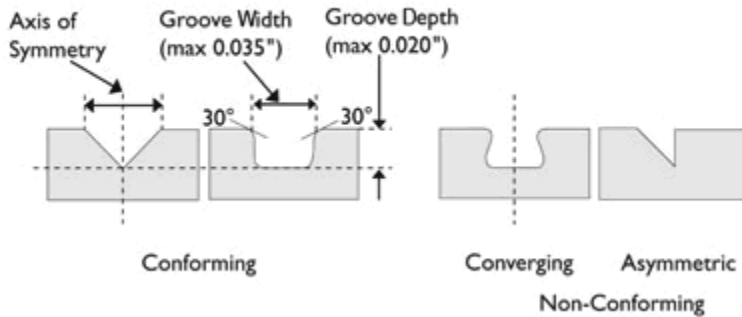
If a club has grooves and/or punch marks in the impact area they must meet the following

specifications:

(i) Grooves

- Grooves must be straight and parallel.

- Grooves must have a plain*, symmetrical cross-section and have sides which do not converge (see Figure XI).

Fig. XI

Axis of Symmetry   Groove Width (max 0.035")   Groove Depth (max 0.020")

30°   30°

Conforming

Converging   Asymmetric

Non-Conforming

- The width, spacing and cross-section of the grooves must be consistent throughout the impact area.

- The width (W) of each groove must not exceed 0.035 inches (0.9 mm), using the 30 degree method of measurement on file with the USGA.

- The distance between edges of adjacent grooves (S) must not be less than three times the width of the grooves, and not less than 0.075 inches (1.905 mm).

- The depth of each groove must not exceed 0.020 inches (0.508 mm).

- *For clubs other than driving clubs, the cross-sectional area (A) of a groove divided by the groove pitch (W+S) must not exceed 0.0030 square inches per inch (0.0762 mm^2/mm) (see Figure XII).

Fig. XII

$$\frac{A}{W+S} \leq 0.0030 in^2 / in$$

W   S

A
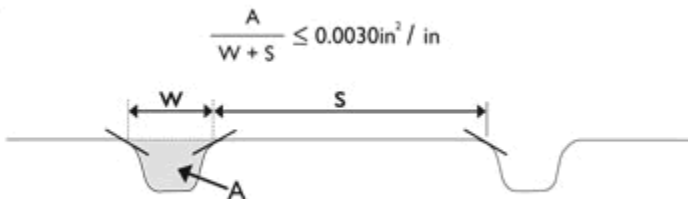
- Grooves must not have sharp edges or raised lips.

- *For clubs whose loft angle is greater than or equal to 25 degrees, groove edges must have an effective radius which is not less than 0.010 inches (0.254 mm) when measured as shown in Fig. XIII, and not greater than 0.020 inches (0.508 mm). Deviations in effective radius within 0.001 inches (0.0254 mm) are permissible.

Fig. XIII

R=0.010"

0.001"

Conforming   Non-Conforming
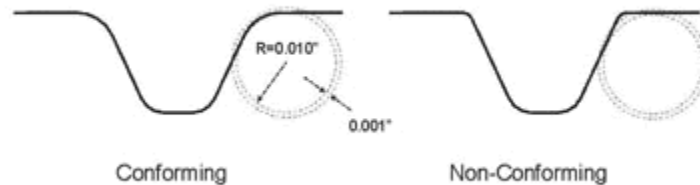
(ii) Punch Marks

- The maximum dimension of any punch mark must not exceed 0.075 inches (1.905 mm).

- The distance between adjacent punch marks (or between punch marks and grooves) must not be less than 0.168 inches (4.27 mm), measured center to center.

- The depth of any punch mark must not exceed 0.040 inches (1.02 mm).

- *For clubs whose loft angle is greater than or equal to 25 degrees, punch mark edges must have an effective radius which is not less than 0.010 inches (0.254 mm) when measured as shown in Fig. XIII, and not greater than 0.020 inches (0.508 mm). Deviations in effective radius within 0.001 inches (0.0254 mm) are permissible.

Note 1: The groove and punch mark specifications above marked with an asterisk (*) apply only to new models of clubs manufactured on or after January 1, 2010 and any club where the face markings have been purposely altered, for example, by re-grooving. For further information on the status of clubs available before January 1, 2010, please refer to the Informational Club Database at www.usga.org.

Note 2: The Committee may require, in the conditions of competition, that the clubs the player carries must conform to the groove and punch mark specifications above marked with an asterisk (*). This condition is recommended only for competitions involving the highest level of expert player. For further information, refer to Decision 4-1/1 in "Decisions on the Rules of Golf.".

NOTE: The specifications for grooves and punch marks on clubs available before January 1, 2010, are set out in Supplement A along with a complete guide as to the procedure for measuring width, depth and separation when in the field. Additionally, clubs where the face

markings have been purposely altered, for example, by re-grooving, must conform to the current groove and punch mark specifications. However, clubs which have only been refurbished back to their original state (e.g., through light sandblasting) may still be eligible for the grace period extended to pre-2010 models.
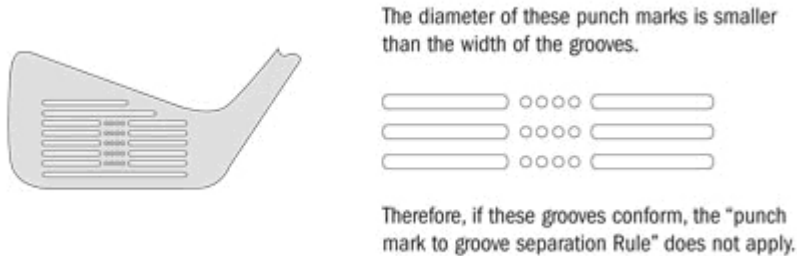
(iii) Groove/Punch Mark Combinations

If punch marks are used in combination with grooves, the following guidelines apply:

Iron Clubs

- *Small punch marks which are in line with a conforming groove, and which would be totally contained within a continuation of the groove, do not have to meet the punch mark to groove specifications. However, if the diameter of such punch marks exceeds the width of the groove, then they must meet the specifications.*

Fig. 40

The diameter of these punch marks is smaller than the width of the grooves.

Therefore, if these grooves conform, the "punch mark to groove separation Rule" does not apply.

- *When measuring the center to center distance between a punch mark and the end of an in-line groove, the center of the groove is deemed to be half a groove width from the end edge of the groove.*

Fig. 41

Groove   w

0.5w

Punch Mark

Center to center distance
must be ≥ 0.168 inches (4.3 mm)
(w = groove width)
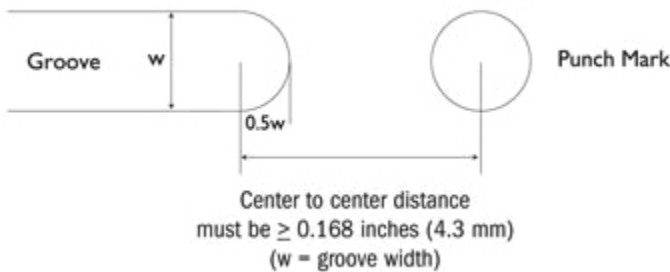
d. Decorative Markings

The center of the impact area may be indicated by a design within the boundary of a square whose sides are 0.375 inches (9.53 mm) in length. Such a design must not unduly influence the movement of the ball. Decorative markings are permitted outside the impact area.

The reason for this rule is to permit small, decorative logos in the center of the face or at the side of the "impact area." Non-conforming markings or logos that marginally encroach on the impact area may be permitted, (i.e., by less than .25 inches (6.35 mm)). However, markings outside the 'impact area' which are designed to unduly influence, or have the effect of unduly influencing the movement of the ball would be contrary to this rule.

Fig. 43
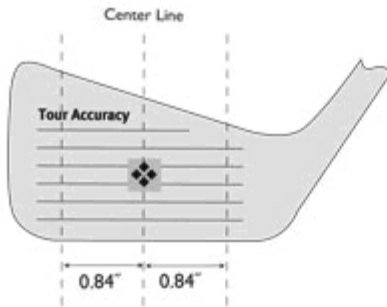
The decorative marking in the center fits into the boundaries of a square whose sides are 0.375 inches (9.53 mm) in length, and thus conforms with the Rules. However, the word "Accuracy", is deemed to significantly encroach on the impact area, and therefore the club is non-conforming.

e. Non-metallic Club Face Markings

The specifications regarding grooves, punch marks and decorative markings that are applicable to metal faces, or faces made from similarly hard materials, do not apply to faces made from other materials and whose loft angle is 24 degrees or less. However, any markings which could influence the movement of the ball are not permitted on such clubs.

APPENDIX B: MESH FINITE ELEMENT ANALYSIS

Mesh Topology	Unit Size (mm)	Beam Thickness (mm)	Max Displacement (mm)	LBSF	Max Lattice Stress (GPa)
Grid	5x5x5	0.3	0.251	0.7	5.4
X	5x5x5	0.3	0.238	1.1	4.8
X	3x3x3	0.3	0.108	4.9	2.0
X	4x4x4	0.3	0.170	2.2	2.8
Star	5x5x5	0.3	0.234	1.1	4.9
W	5x5x5	0.3	0.288	1.0	6.4
Column	5x5x5	0.3	Error	Error	Error
Dark Horse	3x3x3	0.3	0.440	4.4	6.5
Dark Horse	5x5x5	0.3	0.701	1.5	11.4
Dark Horse	5x5x5	0.5	0.406	4.8	5.7
Dark Horse	6x6x6	0.5	0.472	3.0	7.0
Dark Horse	8x8x8	0.5	0.610	2.1	9.7
Vin Tiles	5x5x5	0.3	0.292	2.2	5.3
Cross Pattee	5x5x5	0.3	0.162	1.8	9.2
Soft Box	5x5x5	0.3	0.250	1.6	4.4
Hexagrid	5x5x5	0.3	0.560	0.5	12.9
Snow Flake	5x5x5	0.3	0.410	2.8	11.3
Hexagon	5x5x5	0.3	0.217	2.6	4.4
Octagon	5x5x5	0.3	0.597	1.9	16.4
Octagon	5x5x5	0.5	0.250	5.9	6.8
3D Spider	5x5x5	0.3	0.685	1.5	15.9
3D Spider	5x5x5	0.5	0.332	4.3	9.1
Icosahedron	5x5x5	0.3	0.150	3.5	4.8
Pyritohedron	5x5x5	0.3	0.490	3.7	9.0
Pyritohedron	5x5x5	0.5	0.164	14.6	4.2
Rhombic Dodecahedron	5x5x5	0.3	0.196	2.3	6.0
Crush	5x5x5	0.3	0.776	9.3	6.8
Crush	5x5x5	0.4	0.612	12.3	6.3
Crush	5x5x5	0.5	0.431	18.5	5.0
Crush	6x6x6	0.5	0.425	11.1	7.1
Crush	7.5x7.5.x7.5	0.5	0.709	10.5	5.5
Crush	10x10x10	0.5	0.532	4.2	13.0
Tetra	5x5x5	0.3	0.106	2.3	2.8
Endoskeleton	5x5x5	0.3	0.410	0.8	32.7

Table B1. Finite Element Analysis Output

APPENDIX C: MESH LOADING CONDITIONS

Force Profile:

From Trackman PGA Tour stats[3], ball speed for a sand wedge extrapolated to average of 100mph (44.7 m/s). Ball mass is 45.9g (*Rules of Golf*).

Change in momentum = $m\Delta v$ = (0.0459kg)(44.7m/s – 0m/s) = 2.05173 kg m/s.

Impact time from graph (Roberts 201) = 0.00045s.

Average force = 2.05173 kg m/s/0.00045s = 4559N

Assume maximum force is approximately twice of average force = 9100N = 9.1kN

This is close to the literature value of 8.5-10kN listed by Penner.

Impact angle = Wedge loft – attack angle[4] = 56° - (-5°) = 61°

Normal component = 9100N*cos(61°) = 4410N

Tangent component = 9100N*sin(61°) = 7960N

Impact Area:

Distance compressed given by d = 0.17v for d in mm and v in m/s (Dowell, Krebs 37).

To calculate d, only the normal component of velocity should be used. From the point of reference of the club face, the ball approaches at a velocity equal to the clubhead velocity just prior to impact at an angle of 61°. Average clubhead velocity is 64.4mph (28.8m/s) obtained from player testing.

v = (28.8m/s)*cos(61°) = 13.96m/s

d = 0.17v = 2.37mm

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[3] https://blog.trackmangolf.com/trackman-average-tour-stats/
[4] Attack angle assumed to average equal to pitching wedge attack angle from https://blog.trackmangolf.com/trackman-average-tour-stats/

The radius of the circular contact area, b, can be derived from the distance of mutual approach d and sphere radius R with the following equation (*Interim Report*):

$$b = \sqrt{R \cdot d}$$

Given R = 21.35mm (*Rules of Golf*) and d = 2.37mm,

$$b = \sqrt{21.35mm \cdot 2.37mm} = 7.11mm$$

The force calculated above should be applied over a circular area with radius 7.11mm. The contact area is 159mm².

APPENDIX D: YOUNG'S MODULUS AND POISSON'S RATIO CALCULATION

To calculate the effective Young's modulus and Poisson's ratio of the mesh designs, a 100kN load was applied to the top face of a 1x1x1cm cube of each mesh design with 1mm skin for a stress of 1GPa. For the X topology mesh, a 10kN load was applied (for a stress of 100MPa) instead as a load of 100kN resulted in an LBSF of less than 1. Deformation in the longitudinal and transverse directions was measured from the deformation graph output in Within. This was used to calculate Young's modulus and Poisson's ratio via the following equations:

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta L/L}$$

$$v = -\frac{d\varepsilon_{trans}}{d\varepsilon_{axial}}$$

Table D1 below shows deformation (longitudinal and transverse), Young's modulus and Poisson's ratio for each of the three prototype mesh designs. As a reference, the Young's modulus and Poisson's ratio of stainless steel are 193-200 GPa and 0.30-0.31 respectively.

	Longitudinal Deformation	Transverse Deformation	Young's Modulus	Poisson's Ratio
Crush Topology 5x5x5mm unit size 0.3mm beam thickness	0.68mm	0.22mm	14.7 GPa	0.324
Crush Topology 7.5x7.5x7.5mm unit size 0.5mm beam thickness	0.68mm	0.21mm	14.7 GPa	0.309
Dark Horse Topology 3x3x3mm unit size 0.3mm beam thickness	0.58mm	0.22mm	17.2 GPa	0.379
X Topology 4x4x4mm unit size 0.3mm beam thickness	0.062mm	0.016mm	16.1 GPa	0.258

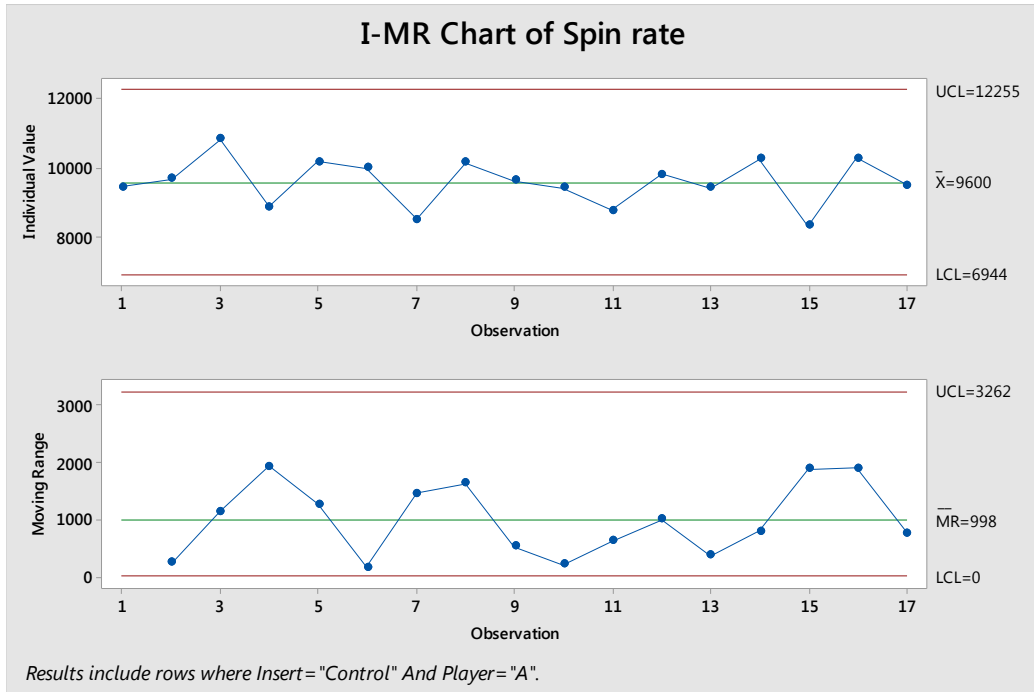**Table D1. Young's Modulus and Poisson's Ratio Calculation**

Figure E1. Control Insert, Player A

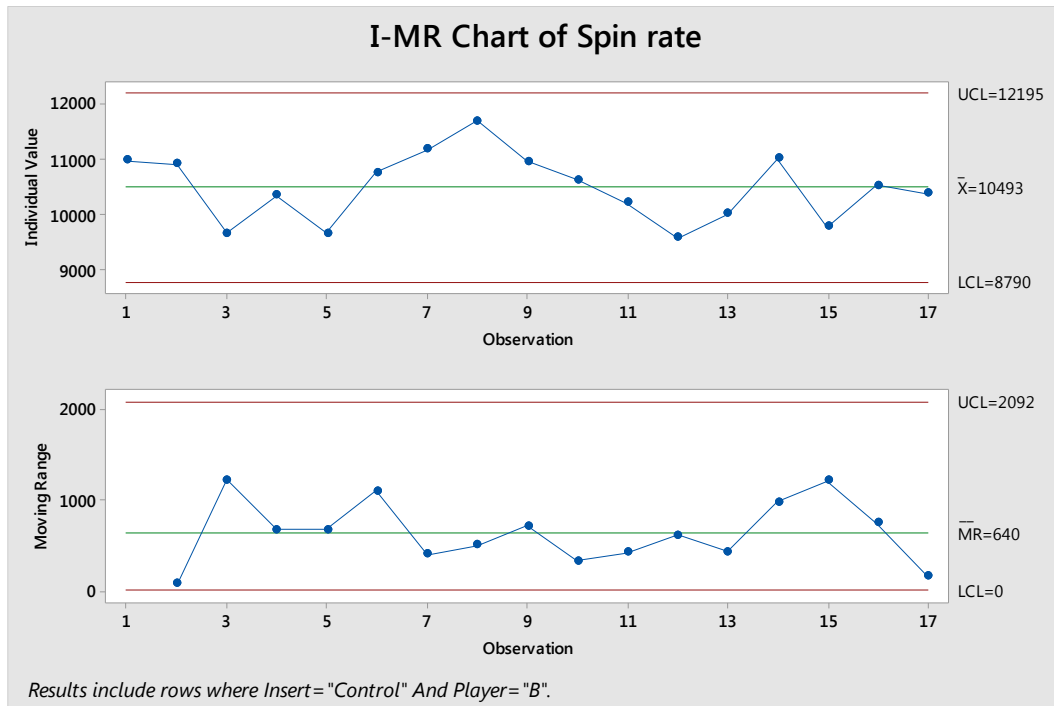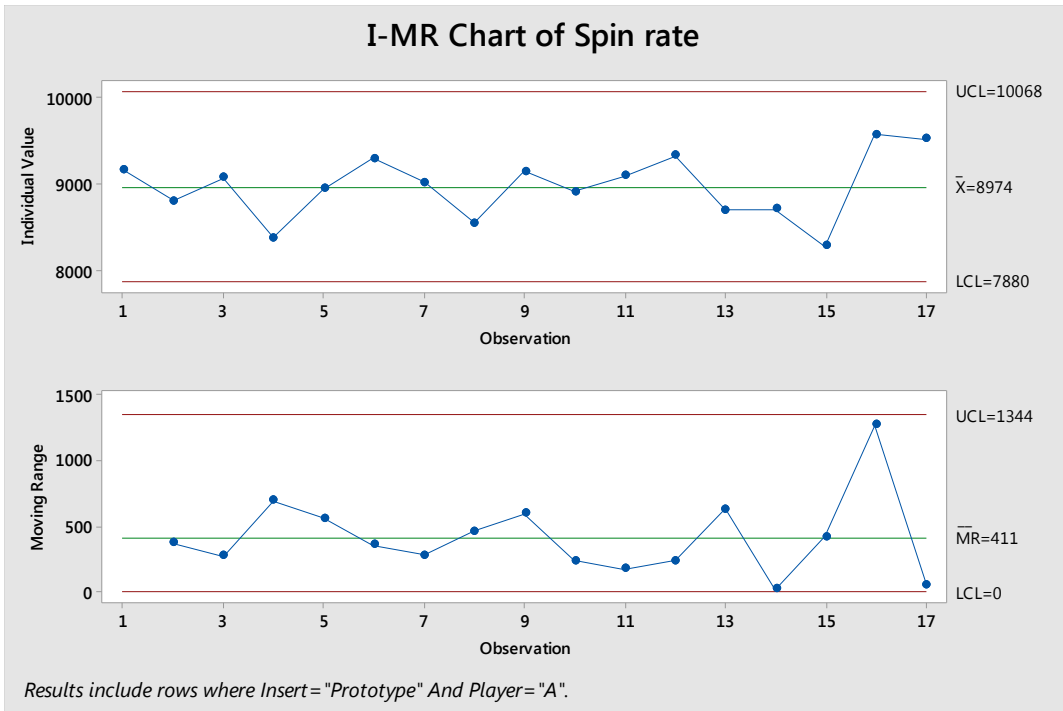**Figure E2. Control Insert, Player B**

Figure E3. Prototype Insert, Player A
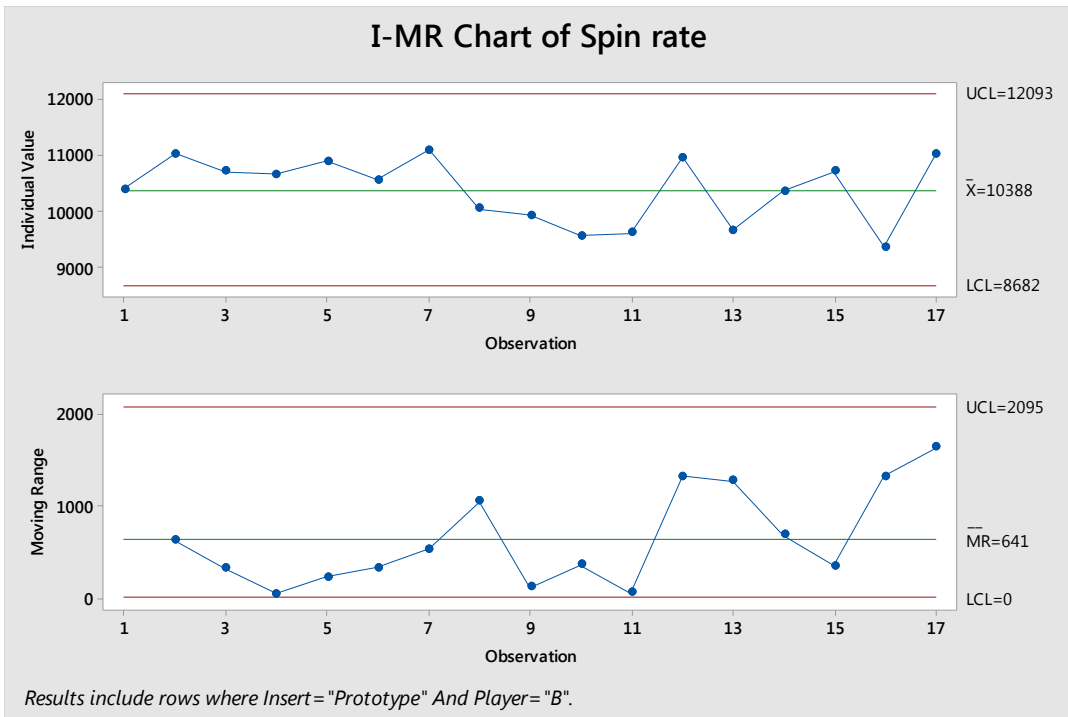

Figure E4. Prototype Insert, Player B

48

Assumptions:

- The population from which the samples were obtained is approximately normally distributed. See Figure F1.

- The samples are independent.

- The variances of the populations are equal. See Figure F2.

Null Hypotheses:

- Population means of the first factor, Insert, are equal.

- Population means of the second factor, Player, are equal.

- There is no interaction between the two factors.

Two-Way ANOVA Table:

General Linear Model: Spin rate versus Insert, Player

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Insert	1	2269207	2269207	7.13	0.010
Player	1	22613791	22613791	71.09	0.000
Insert*Player	1	1153364	1153364	3.63	0.061
Error	64	20358792	318106		
Total	67	46395154			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
564.009	56.12%	54.06%	50.46%

P-value for Insert = 0.010 < 0.05, so the null hypothesis that population means of the Insert factor are equal can be rejected at the 95% confidence level. It can be concluded that the

prototype insert had a significant effect on spin rate. A significantly lower spin rate was
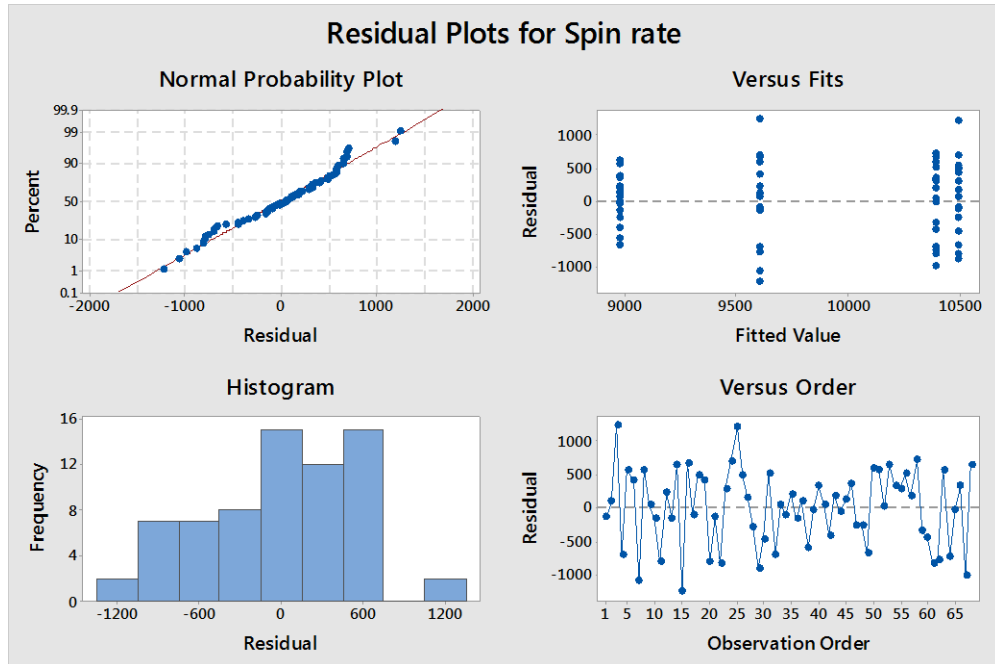
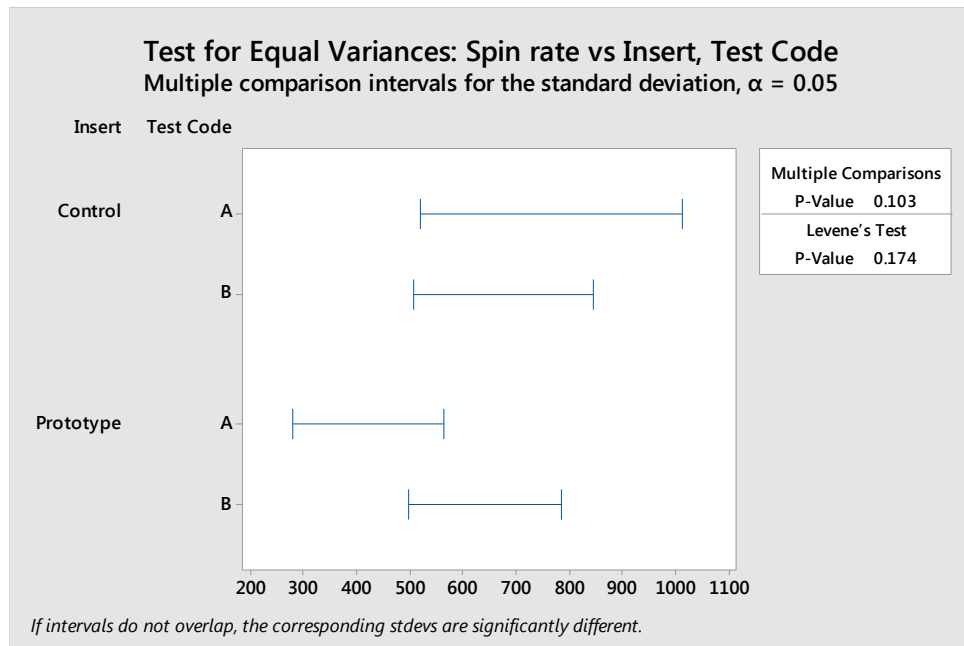observed.

Figure F1. Residual Plots for Spin Rate

Figure F2. Test for Equal Variances

APPENDIX G: COST ANALYSIS SPREADSHEET

SLM Process					
Year	Capital Costs	Labor and Materials (Per Wedge)	Sale Price (Per Wedge)	Quantity	NPV
0	($500,000)	($56)	$200	0	($500,000)
1	0	($56)	$200	1500	$207,216
2	0	($56)	$200	1500	$199,246
3	0	($56)	$200	1500	$191,583
4	0	($56)	$200	1500	$184,215
5	0	($56)	$200	1500	$177,129
					Total
					$459,390

Original Existing with 2 Operators					
Year	Capital Costs	Labor and Materials (Per Wedge)	Sale Price (Per Wedge)	Quantity	NPV
0	0	($17)	$100	0	$0
1	0	($17)	$100	4000	$321,154
2	0	($17)	$100	4000	$308,802
3	0	($17)	$100	4000	$296,925
4	0	($17)	$100	4000	$285,505
5	0	($17)	$100	4000	$274,524
					Total
					$1,486,909

Original Option New Business					
Year	Capital Costs	Labor and Materials (Per Wedge)	Sale Price (Per Wedge)	Quantity	NPV
0	($300,000)	($17)	$100	0	($300,000)
1	0	($17)	$100	4000	$321,154
2	0	($17)	$100	4000	$308,802
3	0	($17)	$100	4000	$296,925
4	0	($17)	$100	4000	$285,505
5	0	($17)	$100	4000	$274,524
					Total
					$1,186,909

Alternative Process					
Year	Capital Costs	Labor and Materials (Per Wedge)	Sale Price (Per Wedge)	Quantity	NPV
0	($520,000)	($25)	$200	0	($520,000)
1	0	($25)	$200	4000	$673,077
2	0	($25)	$200	4000	$647,189
3	0	($25)	$200	4000	$622,297
4	0	($25)	$200	4000	$598,363
5	0	($25)	$200	4000	$575,349
					Total
					$2,596,276