SECOND REPORT ON THE STUDY OF SPIN GENERATION

January 12, 2007

1. SUMMARY

The dynamics of oblique impact between the golf ball and club head are complex and have been the subject of investigation for a long time. However, recent work on the behaviour, of the golf ball in particular, has extended the knowledge considerably. This understanding has prompted a thorough review of the effect of club head face treatments and how they have evolved since the common use of V-shaped grooves.

This research was initiated with a series of player tests that were conducted in order to provide a benchmark of performance from various lies under playing conditions. Starting with un-grooved, muscle-back, forged heads, two sets of irons were fabricated; one having traditional V-shaped grooves and the other having U-grooves with dimensions that would be considered at the limit of conformance. The playing properties of the clubs were otherwise identical. Additionally, balls were selected that were representative of those used on tour in the modern era and the era prior to the common use of U-grooves. Players hit shots from both clean, dry lies and from the rough. Data on the club head presentation and the ball launch were collected.

It was clear from the player data that the configuration of modern club faces has significant performance improvements over the traditional V-shaped groove in grassy lies. For some lofts, it was found that spin using the U-groove club in the rough was actually higher than from a clean lie.

The player data and the equipment used for the player testing were next used in the laboratory to establish that two different materials could be used to mimic the effect of grassy lies on the impact between the club and the ball. Using real grass in the laboratory is not feasible given the number of tests that were planned. Therefore, the use of these grass surrogates permitted oblique impact experiments to be conducted in an efficient and repeatable manner.

Previous work had established that the performance of face treatments of club heads could be reasonably described by a number of parameters such as groove shape, edge radius, groove width, groove depth, groove spacing and land area roughness. In order to better understand

how each of these factors affects the performance of the club face, a series of test plates was designed and fabricated. This first set of plates (Phase I) was designed to vary the individual groove design parameters independently. Each of these plates was tested at a variety of angles using both grass surrogate materials. This testing revealed that the total cross-sectional area of the grooves in the impact area (controlled by groove shape, width, depth and spacing) had a direct effect on the resulting spin. Additionally, it was found that the sharpness of the grooves had a large effect when the groove sidewalls were steep. The effect of edge radius diminished as the groove shape transitioned towards a V-groove profile. To complement the experimental work, various models were used to provide a framework for interpreting the results of the plate impact tests.

With the Phase I plates serving as a guide, a second set of test plates (Phase II) were designed to have the performance of the V-groove but without necessarily having a V-groove profile. Groove design parameters were varied simultaneously to achieve this objective. Results from both sets of tests, Phase I and Phase II, were then combined and it was found that for plates having an edge radius of about 0.010–in or larger, the spin may be estimated from the total cross-sectional area in the impact zone. In addition to this, a more focused testing of groove characteristics and a wide range of golf balls were also evaluated to ensure that spin generation is well understood for ball/groove combinations.

It was also recognised that the launch of the ball is only a portion of the golf shot. Therefore, studies of the aerodynamics and trajectories of iron shots, as well as the bounce and roll behaviour upon impact with the turf, were also undertaken.

Finally, a series of player tests, which encompassed both touring professionals and average golfers, was undertaken to confirm the conclusions reached from the testing of the various Phase I and II plates under laboratory conditions.

For these player tests, a selection of clubs; some with U-grooves, some with V-grooves, and some designed to perform like V-grooves, were tested by players from a professional golf developmental tour, PGA Tour players, and amateur golfers. The launch conditions, measured by a radar tracking unit, were obtained from fairway lies and from the light rough.

The results of the player tests confirmed the laboratory plate testing and demonstrated a distinct difference in spin performance between the U- and V-grooved clubs in the hands of professional golfers, as well as amateur golfers, out of the light rough. The test results demonstrated that there is an appreciable difference in spin rate achieved using U-grooved clubs with urethane covered balls over spin rates with V-grooved clubs. The U-groove club and urethane covered ball combination consistently achieved higher spin rates. These tests also showed that equipment could be manufactured with modified groove configurations that were not V-shaped yet performed like traditional V-groove clubs when used from lies in the light rough.

The amateur player tests revealed that there is only minimal difference in spin rates achieved by amateur golfers when using U- and V-grooved clubs in combination with Surlyn covered balls. The urethane covered ball when used in combination with the U-groove club did show higher spin than the V-groove, the spin performance of a urethane covered ball in concert with a V-groove has very little advantage over a Surlyn covered ball with either groove configuration.

The reduced spin that results from V- and V-like groove profiles, along with changes in the launch angle, affect the trajectory of the ball and thus the conditions (landing angle, spin rate and velocity) of the ball when it impacts the green. The landing conditions of balls struck with V- or V-like grooves lead to significant increases in the total bounce and roll that the ball experiences when it impacts the green when compared to U-grooves.

2. INTRODUCTION

A significant component of the mandate of the technical staff for golf's ruling bodies is to undertake basic research studies on the mechanics and dynamics of the game. One aspect of particular interest is the oblique impact between lofted clubs and the ball under clean and grassy conditions. This topic received considerable attention in the late 1980's.

Recently both experimental and analytical works were undertaken to advance understanding of the behaviour of the golf ball in oblique impacts. In order to extend this work to include the effect of the face treatments of club heads, a comprehensive study was initiated. This study was intended to build upon previous work on the subject and to establish a thorough understanding of how such face treatments affect the launch of the ball and from that, the trajectory and bounce behaviour on impact with the turf.

3. PROJECT OUTLINE

Additional detail for the overall project is presented in the first interim report on the study of spin generation[1]. The project is comprised of five main components:

1. Field Benchmark performance testing ***(completed)***
2. Establishment of a surrogate (or surrogates) for grass ***(completed)***
3. Face treatment performance testing ***(completed)***
4. Study the effect of face treatment performance on shot trajectory and landing behaviour ***(completed)***
5. Confirmation of laboratory testing with field testing ***(completed)***

At the time of publication of the first interim report, only the first two components of the project had been completed. They are described in detail in that report and as such will only be summarised here. However, since that time, the remaining components of the project have been completed and these will be detailed in this report.

3.1. Field Benchmark Performance Testing

The first step of this study was to confirm the hypothesis that the modern clubs with U-shaped grooves had significantly improved performance compared to V-shaped grooves and standard sand blasted faces. This performance, from both clean and grassy lies, was definitively established via a field testing program of professional golfers using iron clubs with a range of lofts and:

- V-groove, sandblasted face, balata covered wound balls or;
- U-groove, sandblasted and/or milled face with modern tour ball or;
- No groove, light sandblasted face (in order to establish a lower performance bound).

3.2. Establishing a Grass Surrogate

The use of actual grass to test face treatments in the lab is impractical. From the initial player testing two grass substitute media were established. The spins produced using these two interface materials as a grass surrogate envelope the spins measured during the player testing across all clubs.

3.3. Face Treatment Performance Testing

Considerable work by the USGA had been conducted during the 1980's on the effect of some different face treatment design parameters. Additional preliminary work on the subject had also been conducted by both governing bodies. The observations made in these previous studies were reviewed and provided the basis for a range of face treatments.

In the first phase of the laboratory performance testing, four basic profiles were created, characterised by dimensions that are at, or near, the limits currently specified by the Rules of Golf. These include (all with moderately sandblasted faces Ra ~ 120 μin):

- U-groove (90° groove sidewalls), with 0.010-in edge radius, 0.035-in wide and 0.020-in deep, 0.140-in groove spacing
- V-groove (55° groove sidewalls), with 0.010-in edge radius, 0.035-in wide and 0.020-in deep, 0.140-in groove spacing
- Intermediate groove (65° groove sidewalls), with 0.010-in edge radius, 0.035-in wide and 0.020-in deep, 0.140-in groove spacing
- Intermediate groove (75° groove sidewalls), with 0.010-in edge radius, 0.035-in wide and 0.020-in deep, 0.140-in groove spacing

The design parameters of the base profiles were then varied in a systematic manner such that the effect of each parameter was isolated. The parameters studied are shown schematically in Figure 3.3.1. As a result of modifying each of the design parameters independently, seventy individual plate designs were developed. Wire EDM was used to create these profiles.

Each of the plates was tested at four angles with two types of grass surrogate media. Impact speeds were set to be consistent with the impact angle.

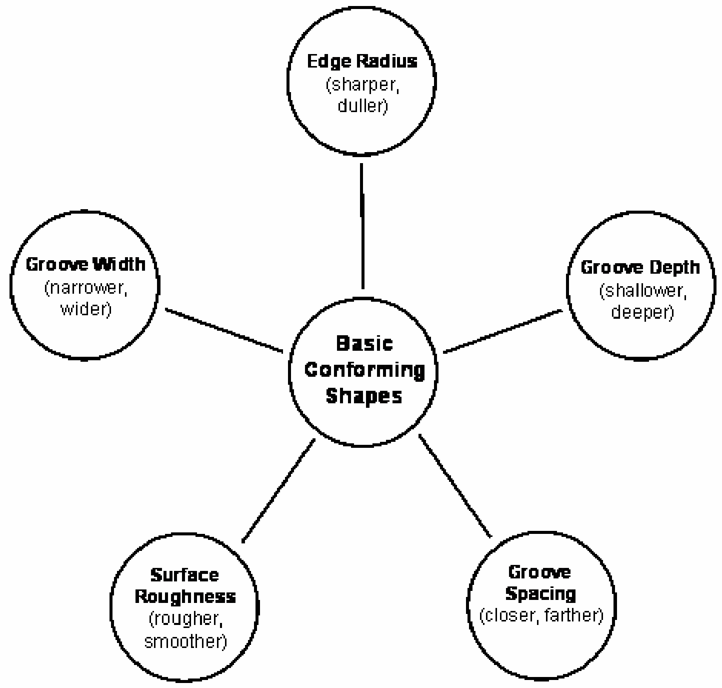


Figure 3.3.1: Plate testing experimental parameters

The testing of the Phase I plates isolated each of the groove parameters independently and their effect on spin was determined. From these results a linear correlation was developed that included the key findings from the Phase I testing.

The second phase of this portion of the project was to combine variations in groove parameters with the purpose of reducing the spin performance of groove profiles that were not V-shaped to that of the V-groove. The correlation developed from the Phase I plate results was then used to generate plate designs where multiple characteristics of groove profiles were varied simultaneously to achieve spin performance close to that of the V-groove. Twenty five additional plates were manufactured.

3.4. Evaluation of the Effect of Face Treatments on Spin

Upon completion of the Phase I and II plate testing of the face treatments, various conclusions could be made about the effectiveness of the range of face treatments. From these conclusions a set of test clubs was designed and fabricated with groove configurations that were not V-shaped but that exhibited V-like groove performance in the laboratory testing with a grass surrogate. These clubs were used for player testing with both professional and amateur golfers to verify the laboratory results and the conclusions reached based on those results.

3.4.1. Consideration of Additional Ball Type

Previous research has been conducted considering the properties of the ball on oblique impact. This research was comprised of quantifying the effects of, grooved versus un-grooved, and roughened versus smooth plates, on the spin magnitudes of different types of golf balls at different angles of incidence (loft) and velocity.

In this portion of the project a subset of the Phase I and II test plates described above were tested with different types of solid golf balls, encompassing a range of construction types and cover materials

3.5. Ball Aerodynamics and Turf Impact

The face treatments on a club affect the launch conditions of the ball and thus both the ball flight trajectory and the resulting bounce and roll on the turf. Studies of ball aerodynamics for iron trajectories and the subsequent impact with the turf were also undertaken.

The experimentally determined launch conditions resulting from the impact of balls with golf clubs, in both wet and dry conditions, and with U- and V-grooved faces, were used to determine the aerodynamic coefficients of lift and drag for two types of golf balls over a broad range of speeds and spins. This aerodynamic model was then used to generate the turf impact conditions (speed, angle and spin) for a series of tests to determine how the ball would bounce and roll on a surface representative of a championship quality green.

3.6. Project Overview

Figure 3.6.1 shows schematically the project tasks.

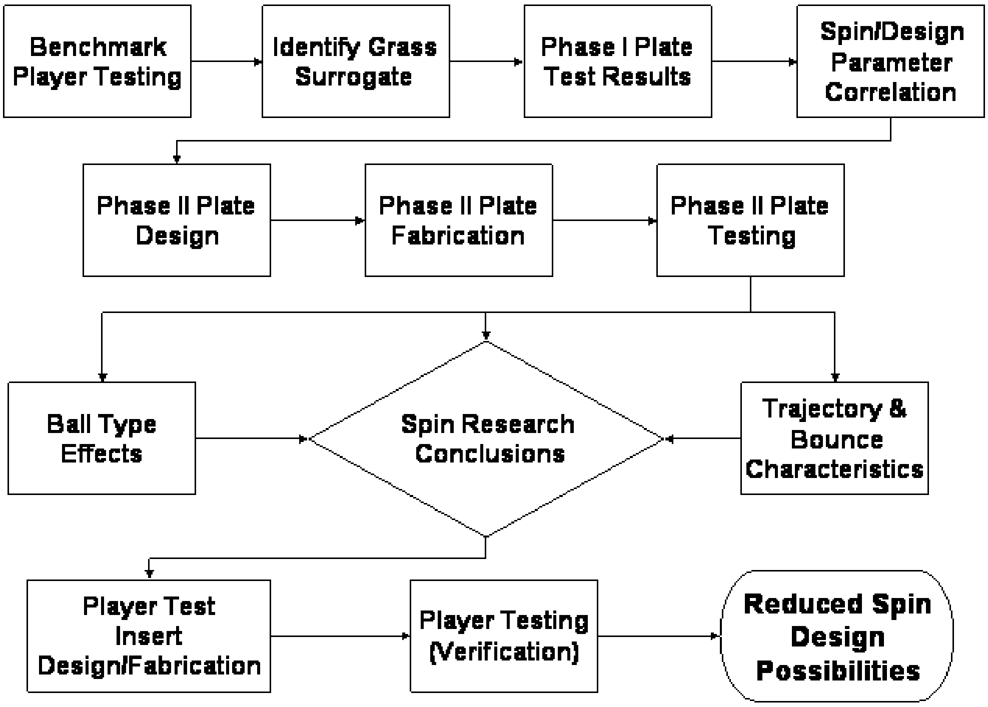


Figure 3.6.1: Project flowchart

4. BENCHMARK PLAYER TESTING

The objective of the benchmark player testing was to obtain launch conditions using equipment representative of today's conformance limits and that of the period prior to the common use of U-grooves.

Three sets of clubs (each comprised of 5 and 8 irons and a sand wedge) were produced with grooves representative of the two eras of interest. Balls typical of those two periods, a wound, balata ball and a modern, multi-layer urethane covered ball, were selected based on a previous study (see Section 4.1.4). A third set of irons was used having no grooves (but with typical sandblasted face roughness) to provide an indication of the practical limit of groove specifications. Impact conditions, determined using high speed video, and the launch conditions, measured by a radar tracking unit, were obtained from both fairway and light rough lies.

Figure 4.1 shows the average results for the two ball/groove combinations in both the dry and the rough from the benchmark player testing. The confidence intervals are also shown. (Note: Unless otherwise specified, all confidence intervals shown in this report are at the 95% confidence level.)

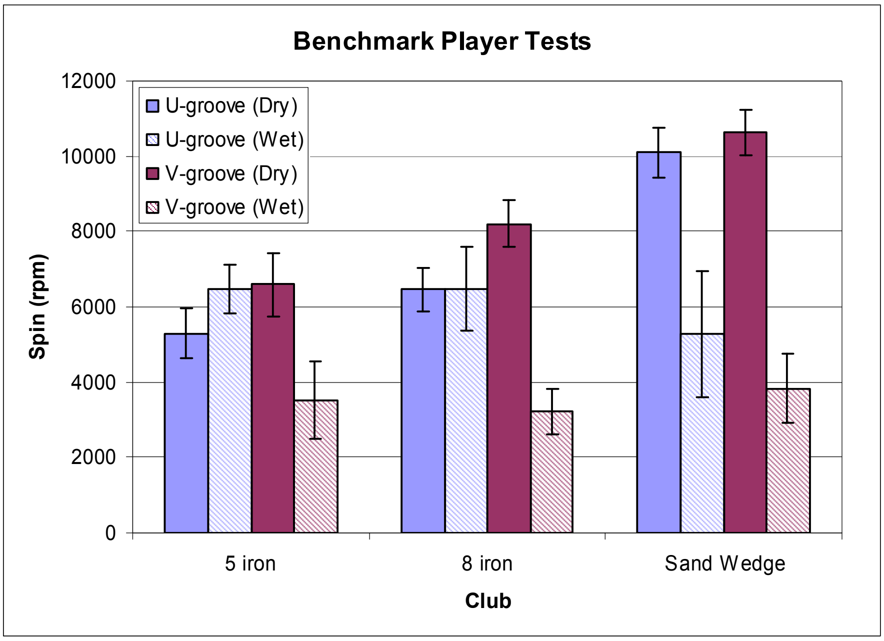


Figure 4.1: Player result averages

The results of the benchmark testing showed that, in the dry condition, the balata ball/V-groove combination spun more than the modern combination at all lofts. However, the modern ball/U-groove combination spun more out of the rough lie than the balata ball/V-groove combination at all lofts. It was also observed that the modern equipment had the potential to actually spin more out of the rough than from a dry lie. This last result, whilst being somewhat counterintuitive was well predicted by various models.

The first interim report contains a full report on the benchmark player testing.

5. Establishing a Surrogate Material for Grass

It has been observed that it is difficult to maintain consistency over time when using actual grass as a test medium for laboratory investigations. Therefore, it was necessary to identify a suitable replacement that behaved in a similar manner to grass and that captured some of the important impact phenomena observed when testing in grassy conditions. To that end, a number of interfacial materials were tested using the U- and V-groove clubs from the benchmark player testing. Two grass substitute media were established. The two materials chosen were wet newsprint and a wet fabric (which was slitted for the testing); DuPont Sontara. The spins produced using these two interface materials, as a grass surrogate, enveloped the spins measured during the player testing across all clubs.

The first interim report contains a full report on the testing to select a grass surrogate.

6. Plate Testing Methodology

The objective of this portion of the project was to provide a broad assessment of the effects of the various groove and face treatment parameters on spin in the presence of an interfacial material (representative of grassy lies). For Phase I of the plate testing, seventy test plates were fabricated. The Phase I plates isolated each of the groove parameters independently so that their effect on spin could be determined. In Phase II of the plate testing the plates were designed by simultaneously varying multiple groove parameters of grooved plates that did not have a V-shaped groove profile in order to achieve spin performance close to that of the V-groove. Twenty five additional plates were manufactured for this phase of the plate testing.

6.1. Equipment

Plates for both Phases I and II were fabricated using the wire EDM method on 17-4 stainless steel in the annealed condition. Figure 6.1.1 shows the cross-section of the basic groove profiles of the test plates. The wire EDM method proved to be an excellent method of producing such plates because (i) the machining is highly accurate, (ii) individual cutters are not required for each groove profile and (iii) the required lead time from design to finished product is very short. In addition to the machining of the grooves, the faces of the plates were abrasive blasted or milled.

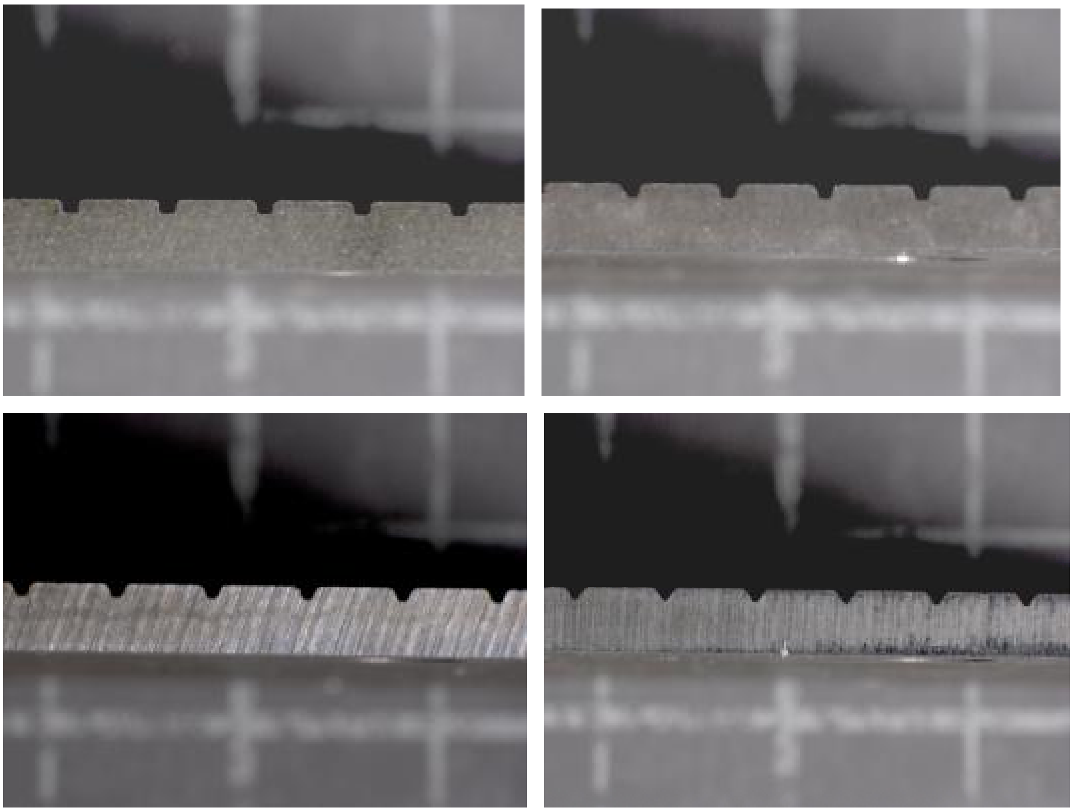


Figure 6.1.1: Cross section of the basic profiles of the grooved test plates (B-series shown)

All plates had six mounting holes that matched holes in a base plate which in turn was affixed to a multi-axis force transducer. This entire assembly was bolted to a massive block attached to an adjustable universal box table. The force transducer permits the normal and tangential direction force time histories to be recorded. Figure 6.1.2 shows a typical plate installed on the transducer/block in an oblique orientation.

A popular three-piece tour ball with a urethane cover (U3P) was used for the testing of the Phase I and II plates.

Figure 6.1.2: Grooved test plate oblique impact test setup

6.2. Impact Conditions

It was intended that the oblique impacts be representative of impacts in playing conditions. Specifically, the impact speed V_{in} (in feet per second) decreases with impact angle θ_{impact} (in degrees) according to:

$$V_{in} = 133.4 - 0.65\theta_{impact}, \quad (6.2.1)$$

which is depicted in Figure 6.2.1.

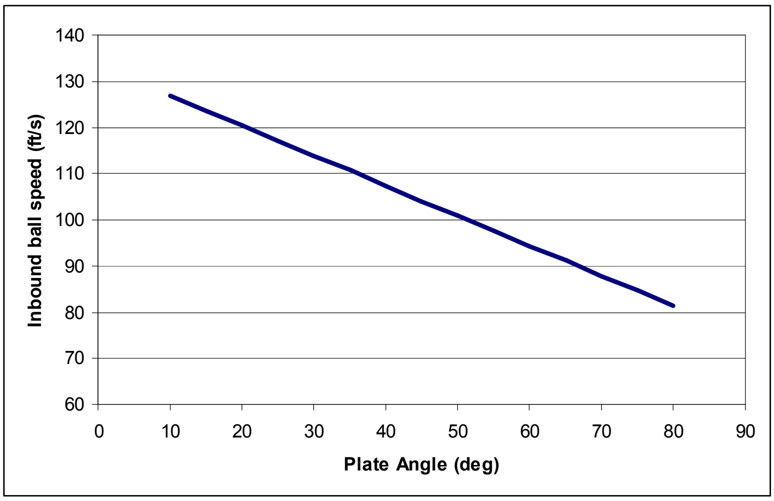


Figure 6.2.1: Inbound ball speed as a function of test plate angle

6.3. Data Collection

The inbound and outbound speed, angle and spin rate were captured using an automated camera system for every shot. At each test condition, shots were fired until the confidence interval for the mean of the outbound spin rate was less than or equal to 300 revolutions per minute. Force time histories from the multi axis force transducer were captured for one impact at each test condition. An example of such a time history is shown in Figure 6.3.1 (for a plate loft angle of 60 degrees).

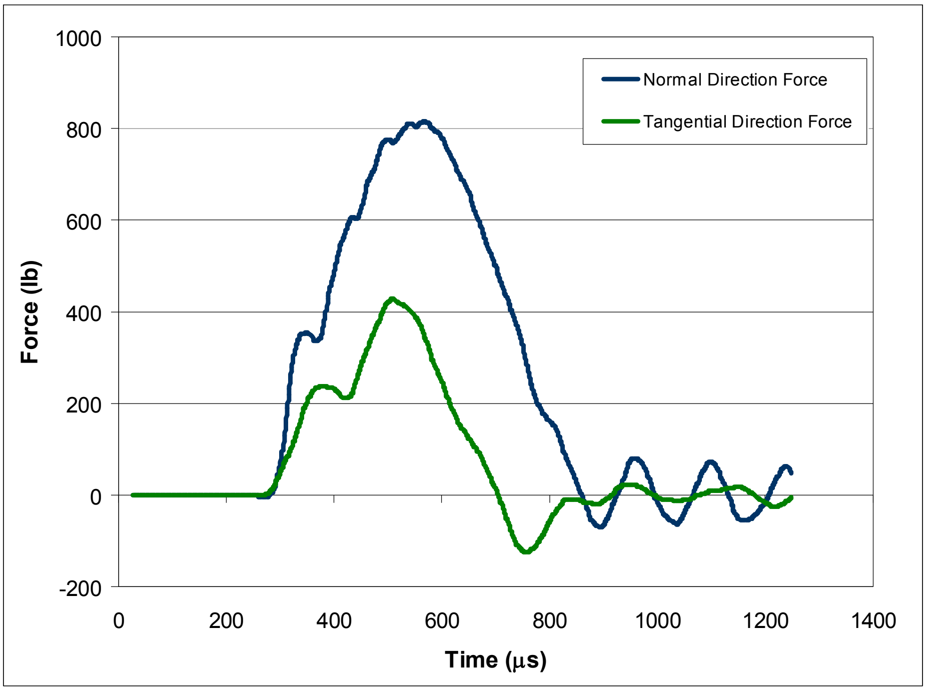


Figure 6.3.1: Example force time history (60 degree plate loft angle)

6.4. PHASE I PLATE TESTING

In the following sections the spin results for the Phase I plates will be presented for tests conducted over a range of angles and with wet newsprint as the grass surrogate. Complete results, including data for the tests using Dupont Sontara are given Appendix A.

6.4.1. Base Plates (B Series)

The base plates were comprised of four different groove profiles where the sidewalls transitioned from a true U-groove to a true V-groove. The dimensions of the grooves for the base plates are given in Table 6.4.1.1

Table 6.4.1.1: B-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width* (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
B100	90 (U)	0.030	0.020	0.010	0.140
B200	75	0.030	0.020	0.010	0.140
B300	65	0.030	0.020	0.010	0.140
B400	55 (V)	0.030	0.020	0.010	0.140
B000	Grooveless				

* All widths in this study measured using forty five degree tangent lines (see Appendix A)

Figure 6.4.1.1 shows the spin results for the base plates with wet newsprint.

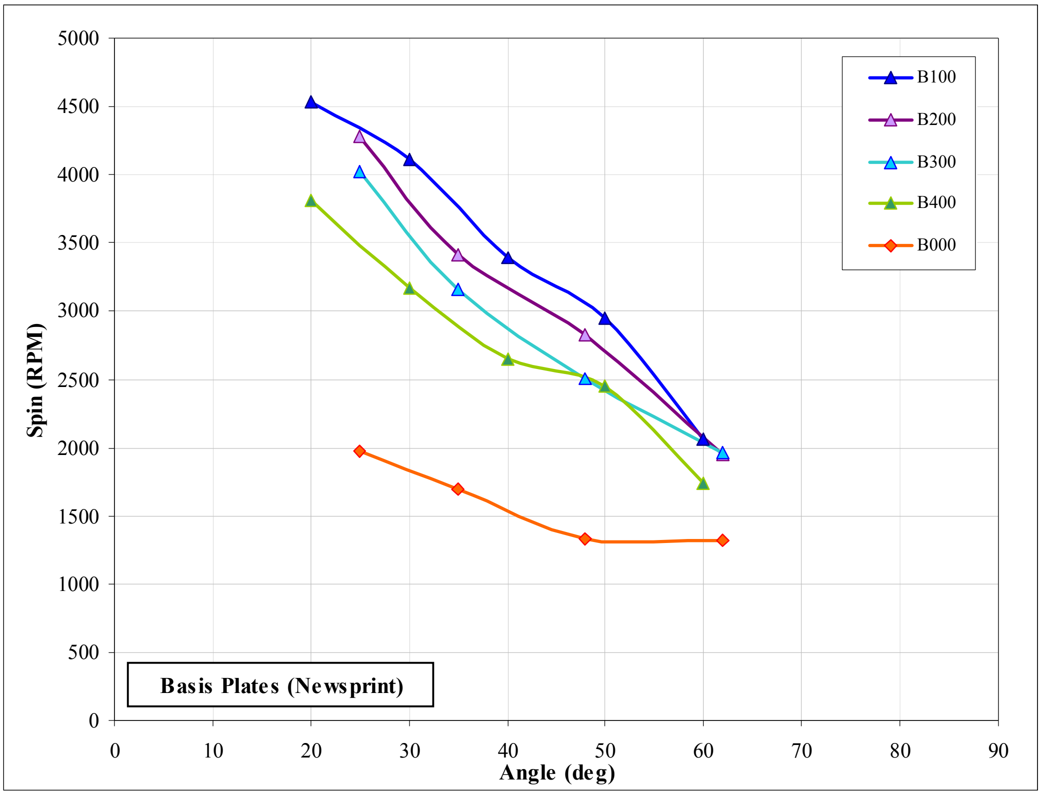


Figure 6.4.1.1: Spin results for Base plates (wet newsprint material)

As observed in the benchmark player testing the U-groove (B100) is superior to the V-groove (B400) at all angles. The semi-U (B200) is close in performance to the U-groove whilst the semi-V (B300) is close in performance to the V-groove. The grooveless plate (B000) performed worse than all of the grooved plates.

The results with the Sontara were not as systematic as the newsprint. The B100, B200 and B300 were indistinguishable from each other. The V-groove (B400) performed worse at most angles than the other shapes. Finally, the grooveless plate performed significantly worse than any of the groove shapes.

6.4.2. Edge Radius (R-Series)

In all of the plates, the edges of the grooves meet the land area with a filleted transition. For most plates, the radius of this fillet was 0.010-in. However, this edge radius was varied in the R series plates from 0.0025-in to 0.020-in (note that the B-series complements the R-series by providing the 0.010-in radius plate). The dimensions of the grooves for the R-Series plates are given in Table 6.4.2.1

Table 6.4.2.1: R-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
R101	90 (U)	0.030	0.020	0.0025	0.140
R102	90 (U)	0.030	0.020	0.005	0.140
R103	90 (U)	0.030	0.020	0.015	0.140
R104	90 (U)	0.030	0.020	0.020	0.140
R201	75	0.030	0.020	0.0025	0.140
R202	75	0.030	0.020	0.005	0.140
R203	75	0.030	0.020	0.015	0.140
R204	75	0.030	0.020	0.020	0.140
R301	65	0.030	0.020	0.0025	0.140
R302	65	0.030	0.020	0.005	0.140
R303	65	0.030	0.020	0.015	0.140
R304	65	0.030	0.020	0.020	0.140
R401	55 (V)	0.030	0.020	0.0025	0.140
R402	55 (V)	0.030	0.020	0.005	0.140
R403	55 (V)	0.030	0.020	0.015	0.140
R404	55 (V)	0.030	0.020	0.020	0.140

The complete set of test results for the R-Series plates is given in Appendix A. Figure 6.4.2.1 shows the spin results for the R100-Series plates with wet newsprint. This figure is representative of the conclusions that were reached regarding the effect of edge radius in the Phase I plate testing.

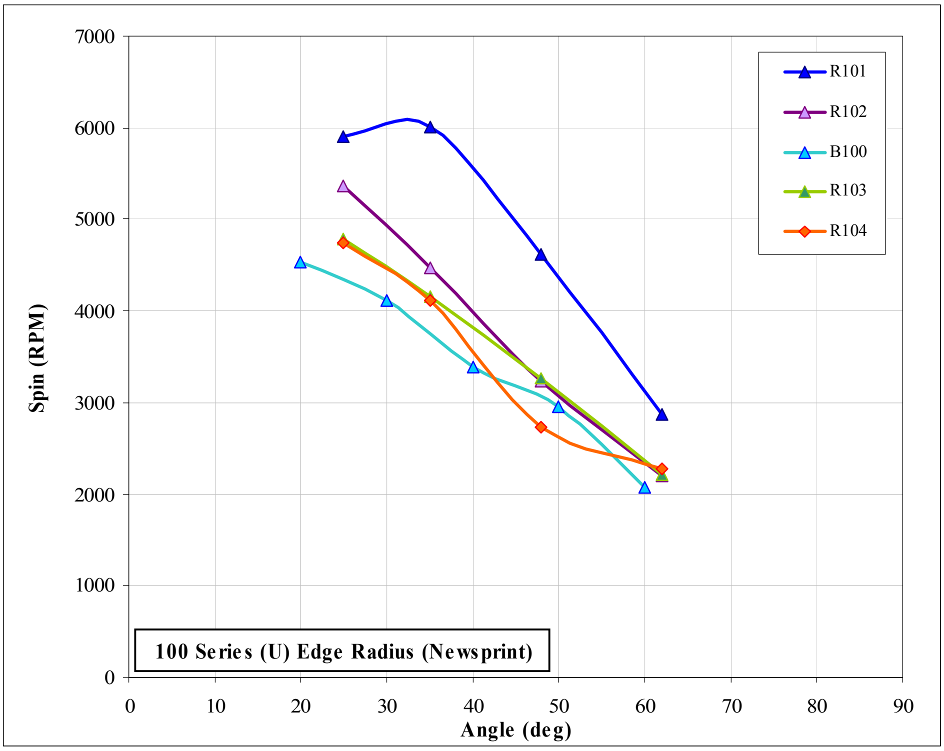


Figure 6.4.2.1: Effect of edge radius on spin results for 100 series plates (newsprint)

The results showed that the effect of edge radius was dependent on the draught angle of the groove sidewalls. It can be seen in Figure 6.4.2.1 that for the R100-series plates, (U-grooves) the sharpest edge radius of 0.0025-in (R101) dramatically increases the spin compared with the base radius of 0.010-in (B100). To a lesser degree, the 0.005-in (R102) radius also improves spin. Edge radii larger than 0.010-in, however, do not appear to have lower performance compared with the base radius.

For the semi U-grooved plates with edge radii of 0.0025-in and 0.005-in there is also an improvement of spin over the 0.010-in, however, transitioning towards the semi-V and V-grooves the effect of edge radius diminishes. Only the sharpest edge radius for the semi-V profile improves spin compared to the duller edges. For the true V-groove edge radius does not affect the resulting spin rate.

An examination of the edge radius results with newsprint interfacial material at a single impact angle, thirty five degrees, demonstrates the effect of edge radius for the various groove shapes,

Figure 6.4.2.2. It is clear in Figure 6.4.2.2 that the edge radius has the greatest effect on the U-shaped groove with diminishing effect as the groove shape transitions towards a V-shape.

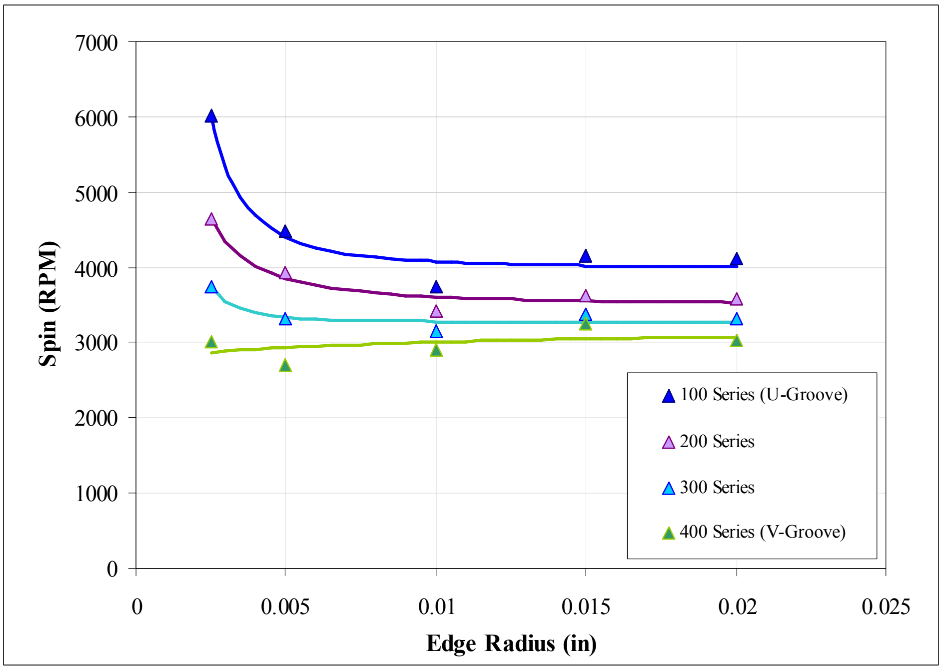


Figure 6.4.2.2: Effect of edge radius on 35 degree spin results (newsprint)

6.4.3. Spacing (S Series)

For purposes of this project, spacing is defined as the centre to centre distance, commonly referred to as the pitch. The current groove specification permits the edge to edge distance to be no closer than three times the width of the groove (as measured from 30 degree tangency points), which itself is limited to 0.035-in. Therefore, for maximum width grooves, the minimum allowable edge to edge distance would be 0.105-in. Equivalently, the minimum allowable pitch of such a configuration would be 0.140-in, which is 0.105-in plus the width of the groove of 0.035-in. The spacing of the S series test plates was varied by ±0.035-in for all four groove shapes. The U and semi-U profiles plates additionally had a spacing of 0.210-in. (It should be noted that these last two plates (S103 and S203) were formally part of Phase II designs but have been included here for comparison purposes.) The dimensions of the grooves for the S-Series plates are given in Table 6.4.3.1.

Table 6.4.3.1: S-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
S101	90 (U)	0.030	0.020	0.010	0.105
S102	90 (U)	0.030	0.020	0.010	0.175
S103	90 (U)	0.030	0.020	0.010	0.210
S201	75	0.030	0.020	0.010	0.105
S202	75	0.030	0.020	0.010	0.175
S203	75	0.030	0.020	0.010	0.210
S301	65	0.030	0.020	0.010	0.105
S302	65	0.030	0.020	0.010	0.175
S401	55 (V)	0.030	0.020	0.010	0.105
S402	55 (V)	0.030	0.020	0.010	0.175

The complete set of test results for the S-Series plates is given in Appendix A. Figure 6.4.3.1 shows the spin results for the S100-Series plates with wet newsprint. This figure is representative of the conclusions that were reached regarding the effect of groove spacing in the Phase I plate testing.

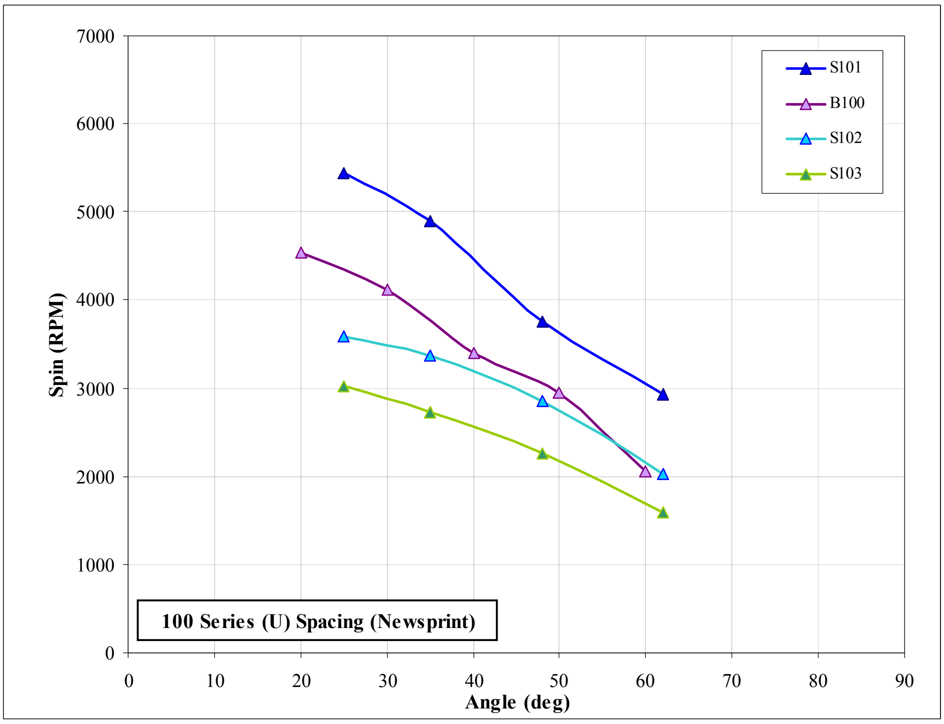


Figure 6.4.3.1: Effect of spacing on spin results for 100 series plates (newsprint)

From Figure 6.4.3.1 it can be seen that decreasing the spacing of the grooves increases the spin performance. This trend is consistent for all groove shapes. The effect of increasing spacing is less certain. In testing at low angles with newsprint, the spin performance of all the groove shapes was reduced with increasing spacing. However, at other angles, and with the Sontara material, increasing the pitch distance from 0.140-in to 0.175-in did not significantly reduce spin. This may be a result of the finite nature of the contact patch. That is, changing the spacing from 0.140-in to 0.175-in may not have consistently increased the number of grooves in contact with the ball. Increasing the pitch distance on the U and semi-U groove profiles to 0.210-in, however, did have the expected result of lowering spin performance.

6.4.4. Depth (D Series)

The limit of groove depth is currently 0.020-in. Test plates were generated with depths reduced to 0.010-in and 0.015-in for all groove shapes. In addition, where possible, groove depths were increased to 0.025-in and 0.0394-in (V-groove depth cannot be increased whilst maintaining a sidewall draught angle of 55 degrees, for example). The dimensions of the grooves for the D-Series plates are given in Table 6.4.4.1.

Table 6.4.4.1: D-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
D101	90 (U)	0.030	0.010	0.010	0.140
D102	90 (U)	0.030	0.015	0.010	0.140
D103	90 (U)	0.030	0.025	0.010	0.140
D104	90 (U)	0.030	0.0394	0.010	0.140
D201	75	0.030	0.010	0.010	0.140
D202	75	0.030	0.015	0.010	0.140
D203	75	0.030	0.025	0.010	0.140
D204	75	0.030	0.0394	0.010	0.140
D301	65	0.030	0.010	0.010	0.140
D302	65	0.030	0.015	0.010	0.140
D303	65	0.030	0.025	0.010	0.140
D401	55 (V)	0.030	0.010	0.010	0.140
D402	55 (V)	0.030	0.015	0.010	0.140

The complete set of test results for the D-Series plates is given in Appendix A. Figure 6.4.4.1 shows the spin results for the D100-Series plates with wet newsprint. This figure is representative of the conclusions that were reached regarding the effect of groove depth in the Phase I plate testing.

Figure 6.4.4.1 shows that for the D100-Series plates with the newsprint interface, the spin is directly controlled by groove depth. This was the case for nearly all the groove profiles with the newsprint interface. As with the edge radius, the thirty five degree impact angle most clearly demonstrates this, Figure 6.4.4.2.

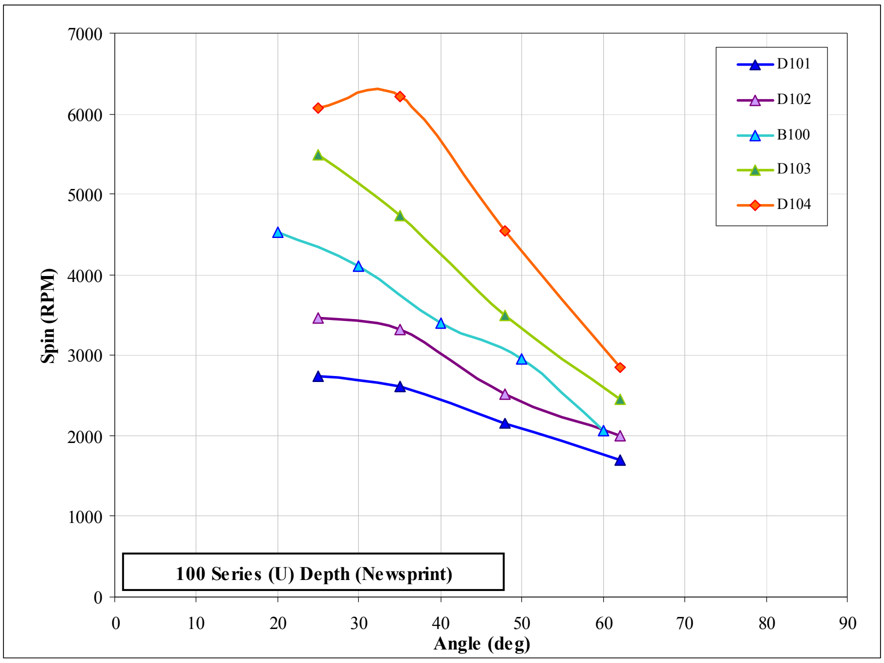


Figure 6.4.4.1: Effect of depth on spin results for 100 series plates (newsprint)

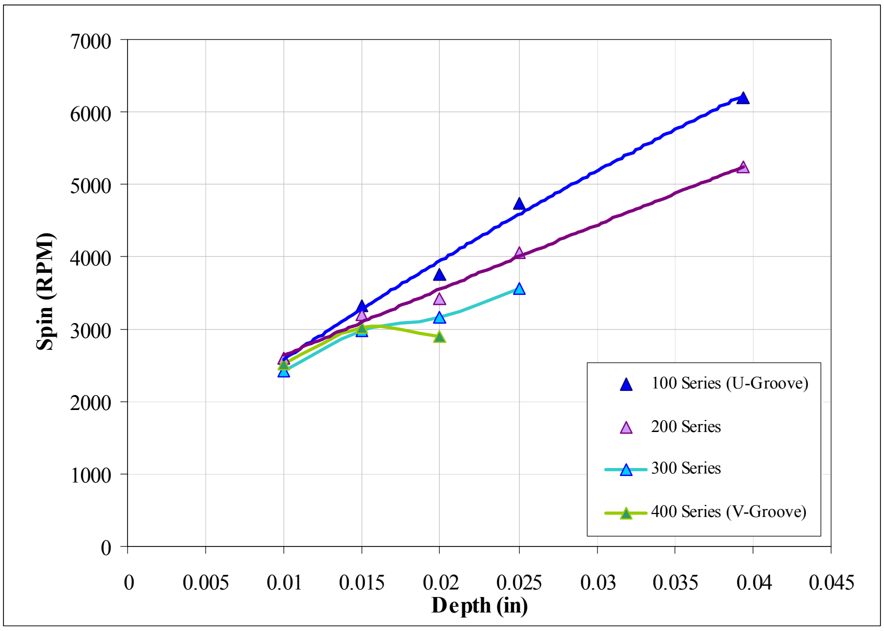


Figure 6.4.4.2: Effect of depth on 35 degree spin results (newsprint)

Figure 6.4.4.2 shows that, except for the V-groove, the spin increases with depth. Generally similar behaviour is exhibited with the Sontara; however, beyond a depth of 0.025-in, no additional benefit was realised.

6.4.5. Width (W-Series)

Groove width is currently limited to 0.035-in measured from the thirty degree tangency points on the edges of the groove. In order to minimise changes in groove cross-sectional area as a function of edge radius, groove widths in this study were measured at the forty five degree tangency points. A groove with a 0.010-in edge radius and a width of 0.035-in measured via thirty degree tangency points would measure approximately 0.030-in wide at the forty five degree tangency points. (The difference in these two measurement techniques is detailed in Appendix A.) Groove widths were varied from 0.020-in to 0.035-in (approximately equivalent to 0.025-in to 0.040-in using thirty degree tangency points) where possible. For example, the V-groove could only be widened whilst maintaining a fifty five degree draught angle. The dimensions of the grooves for the W-Series plates are given in Table 6.4.5.1.

Table 6.4.5.1: W-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
W101	90 (U)	0.020	0.020	0.010	0.140
W102	90 (U)	0.025	0.020	0.010	0.140
W103	90 (U)	0.035	0.020	0.010	0.140
W201	75	0.020	0.020	0.010	0.140
W202	75	0.025	0.020	0.010	0.140
W203	75	0.035	0.020	0.010	0.140
W302	65	0.025	0.020	0.010	0.140
W303	65	0.035	0.020	0.010	0.140
W403	55 (V)	0.035	0.020	0.010	0.140

The complete set of test results for the W-Series plates is given in Appendix A. Figure 6.4.5.1 shows the spin results for the W100-Series plates with wet newsprint. This figure is representative of the conclusions that were reached regarding the effect of groove width in the Phase I plate testing.

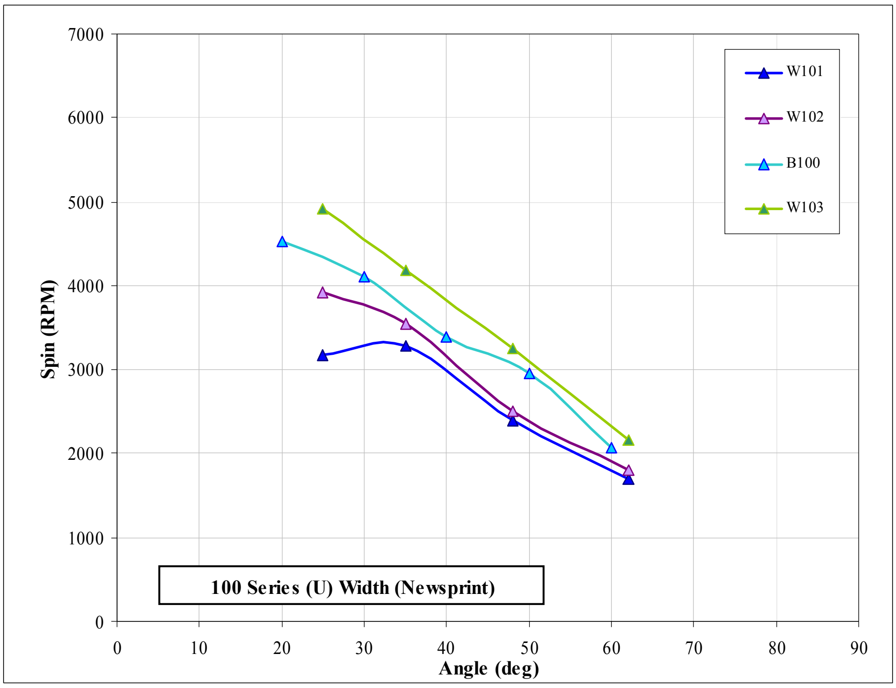


Figure 6.4.5.1: Effect of groove width on spin results for 100 series plates (newsprint)

As with groove depth, spin increases with width. Once again, the thirty five degree impact angle with newsprint clearly demonstrates this effect, Figure 6.4.5.2.

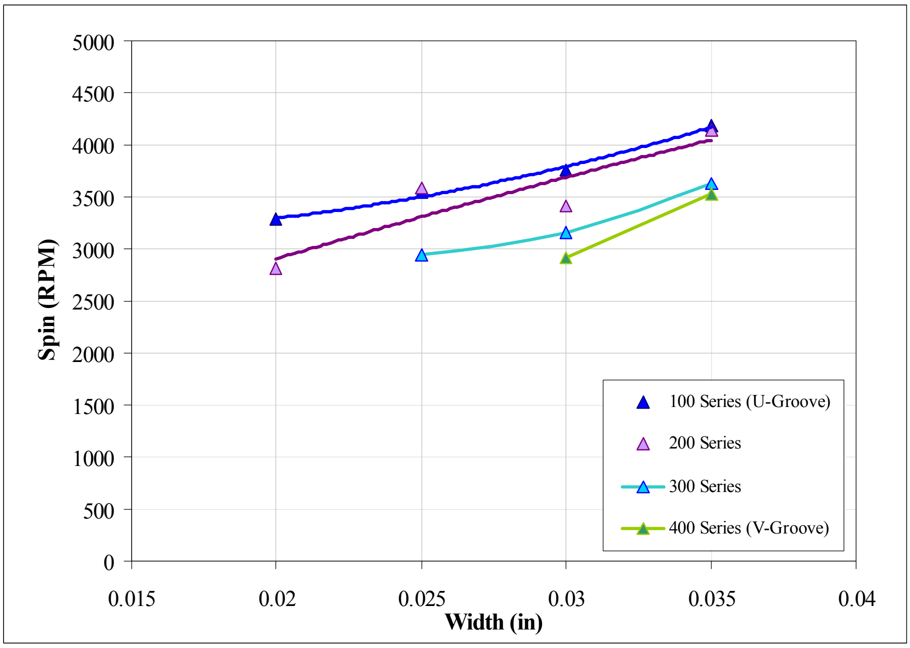


Figure 6.4.5.2: Effect of groove width on 35 degree spin results (newsprint)

6.4.6. Milling (M-series)

A series of plates were milled spanning the range of conformance. They include a grooveless plate, and plates with the four base grooves. The milling was varied from approximately 150-250 micro inches and the milling orientation was varied through three angles; 0°, 45°, and 90°. The dimensions of the grooves and the roughness of the milling for the M-Series plates are given in Table 6.4.6.1.

Table 6.4.6.1: M-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Milling Angle (deg.)	Ra (micro-inches)
M001	N/A	N/A	N/A	0	100
M101	90	0.030	0.020	0	160
M102	90	0.030	0.020	0	190
M103	90	0.030	0.020	0	265
M104	90	0.030	0.020	90	140
M105	90	0.030	0.020	45	190
M201	75	0.030	0.020	0	110
M202	75	0.030	0.020	0	175
M203	75	0.030	0.020	0	410
M301	65	0.030	0.020	0	140
M302	65	0.030	0.020	0	200
M303	65	0.030	0.020	0	250
M304	65	0.030	0.020	90	215
M305	65	0.030	0.020	45	150
M401	55	0.030	0.020	0	150
M402	55	0.030	0.020	0	200
M403	55	0.030	0.020	0	255
M404	55	0.030	0.020	90	215
M405	55	0.030	0.020	45	250

The complete set of test results for the M-Series plates is given in Appendix A. Figure 6.4.6.1 shows the spin results for the M100-Series plates with wet newsprint. This figure is representative of the conclusions that were reached regarding the effect of groove width in the Phase I plate testing.

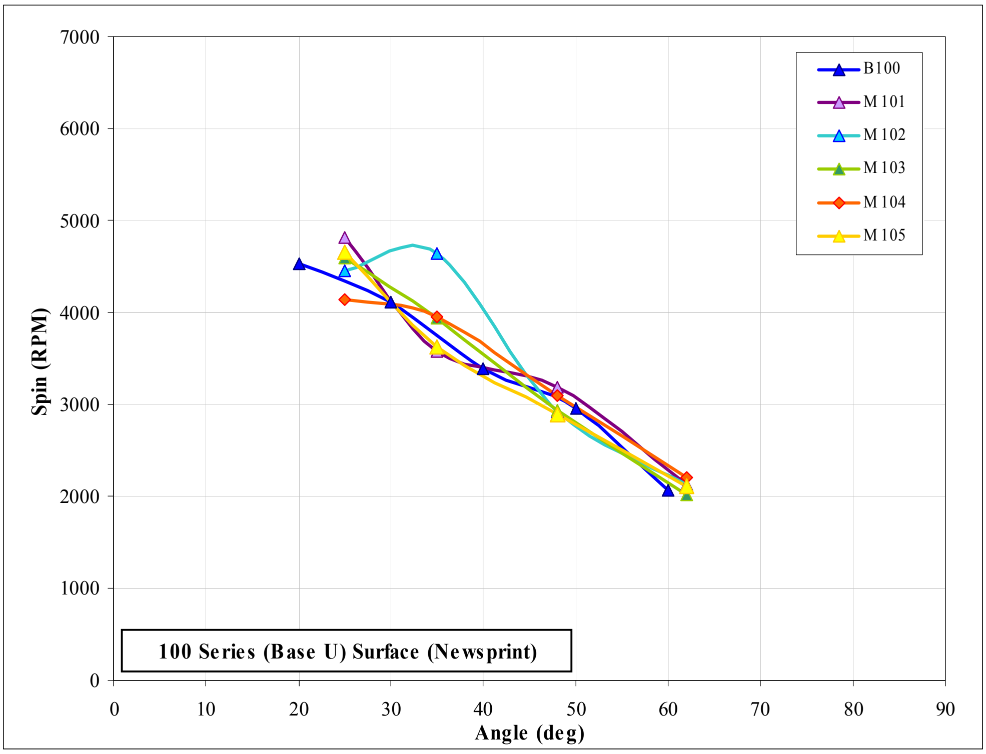


Figure 6.4.6.1: Effect of milling on spin results for 100 series plates (newsprint)

Within the range of conforming milling (Ra=180 micro inches,) the milling had no appreciable effect on the spin in any of the tested milling orientations when using either the newsprint or Sontara as a grass surrogate. The spin did increase moderately for milling that has extreme values of roughness (Ra=400 micro inches).

6.5. Correlation of Phase I Results and Spin Prediction

Spin results from Phase I of the plate testing at thirty five degrees with newsprint were used to relate the groove parameters to spin. (Results at other angles provide similar conclusions.) A linear correlation was developed from these results. This correlation was intended to include the following key findings:

- The spin increases as the groove shape profile transitions from V to U
- Decreasing edge radius increases spin
- Increasing edge radius above 0.010-in has limited effect
- Edge radius has a greater effect for large draught angles
- Decreasing spacing increases spin
- Increasing depth increases spin
- Increasing width increases spin

The data was fitted by an equation given by:

$$\omega_{35^\circ} = 0.12\frac{(\theta_{draught} - 55)}{R_{edge}} + 620000\frac{A}{S} + 1130 \qquad (6.5.1)$$

where ω_{35} is the spin for impacts at thirty five degrees with newsprint interface, $\theta_{draught}$ is the groove sidewall draught angle (degrees), R_{edge} is the edge radius (inches), A is the cross-sectional area of the groove (square inches).

The measured spin is plotted against the spin predicted by Equation (6.5.1) in Figure 6.5.1.

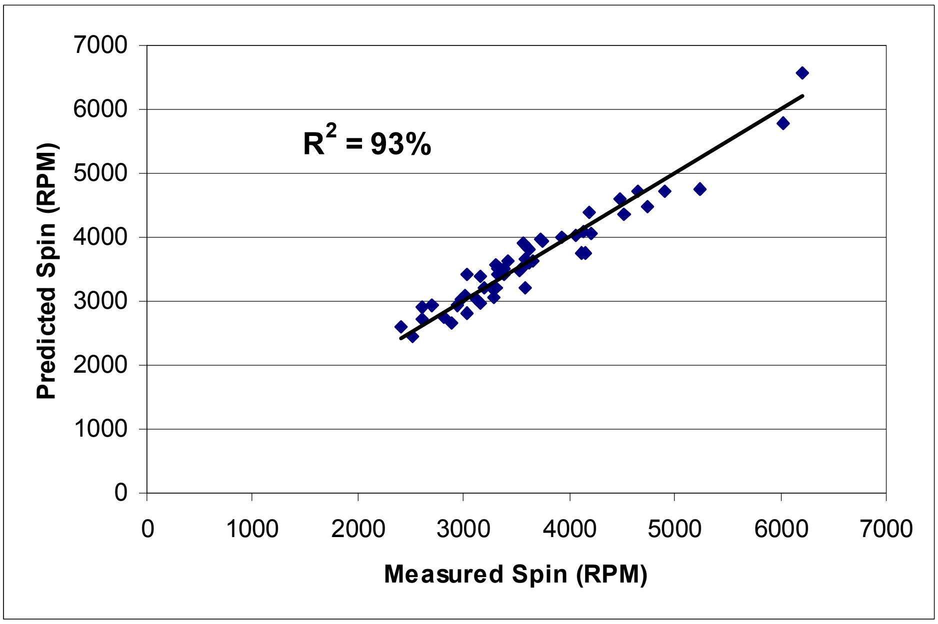


Figure 6.5.1: Performance of spin/groove parameter correlation (Phase I)

It can be seen in Figure 6.5.1 that the correlation fits the measured data very well with a coefficient of determination of 93%. This relationship was used as guidance for the design of the Phase II plates.

6.6. PHASE II PLATE TESTING

The objective of the Phase II plate designs was to combine variations in groove parameters with the purpose of reducing the spin performance of groove profiles that were not V-shaped to that of the V-groove. Equation 6.5.1 was used to generate plate designs where multiple groove characteristics were varied simultaneously to achieve spin performance close to that of the V-groove. Twenty five additional plates were manufactured. The specifications for these plates are provided in Appendix A.

A few additional plates were also created to study minor topics. These include punch marks and grooves with internal shoulders. The performance of these plates will not be addressed here but are discussed in Appendix A.

6.6.1. Phase II Testing Results

The plates in Phase II were tested in the same manner as those in Phase I. Tests were conducted at impact angles of 25, 35, 48 and 62 degrees with both newsprint and Sontara grass surrogate materials. Some of the results of these tests are plotted in Figure 6.6.1.1. The measured spin at thirty five degrees with newsprint material was compared to the target performance, that of the V-groove plate (B400, green bar). The spin of R102 (which would be considered at the limit of the current conformance standard using the "finger" test specified in the Rules of Golf) is also included in red for reference.

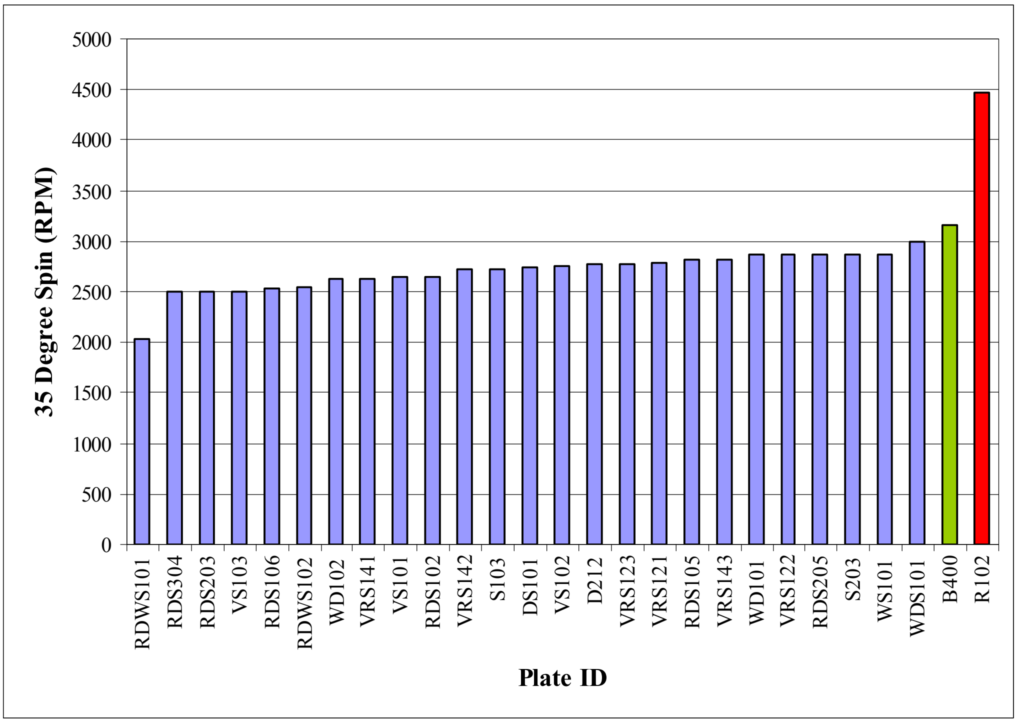


Figure 6.6.1.1: Performance of Phase II (V-groove like) plate designs

The Phase II plates somewhat underperformed the target with an average spin of 2700 RPM for the Phase II designs compared to 3200 for the V-groove plate. This indicates that the groove parameters affect spin somewhat differently when modified simultaneously than was predicted by equation 6.5.1. However, the Phase II plates performed similarly to each other indicating that the principle of predicting spin by the groove specification was sound.

6.7. Ball Construction Type Testing

A popular tour quality ball (three-piece, urethane cover) was used for the testing of the Phase I and II plates. This testing revealed that for some groove profiles, the sharpness of the groove can increase the spin from an oblique impact in the presence of an interfacial material. It has also been observed that this effect depends strongly on the construction of the golf ball. Specifically, it was observed that two similar urethane covered balls performed differently on grooves with small edge radii (sharp groove edges). To quantify this interdependent relationship a series of oblique impact tests was conducted.

Plates having groove edge radii of 0.005-in and 0.010-in and a range of draught angles from ninety degrees (U-groove) to fifty five degrees (V-groove) were tested. The two most shallow groove shapes, sixty five and fifty five degrees, were also tested with edge radii of 0.0025-in. Three ball types were used. A three-piece, urethane covered ball (U3P), a similar, four piece urethane covered ball (U4P), and a two piece Surlyn™ covered ball (S2P). Impacts were recorded at 25, 35, 48 and 62 degrees according to a standardised oblique impact test procedure described previously. Wet newsprint was used as the interfacial material.

The results for the three-piece urethane covered ball (U3P) at the 35° impact angle are given in Figure 6.7.1. Results at other impact angles show similar trends. Complete details of the tests are given in Appendix B.

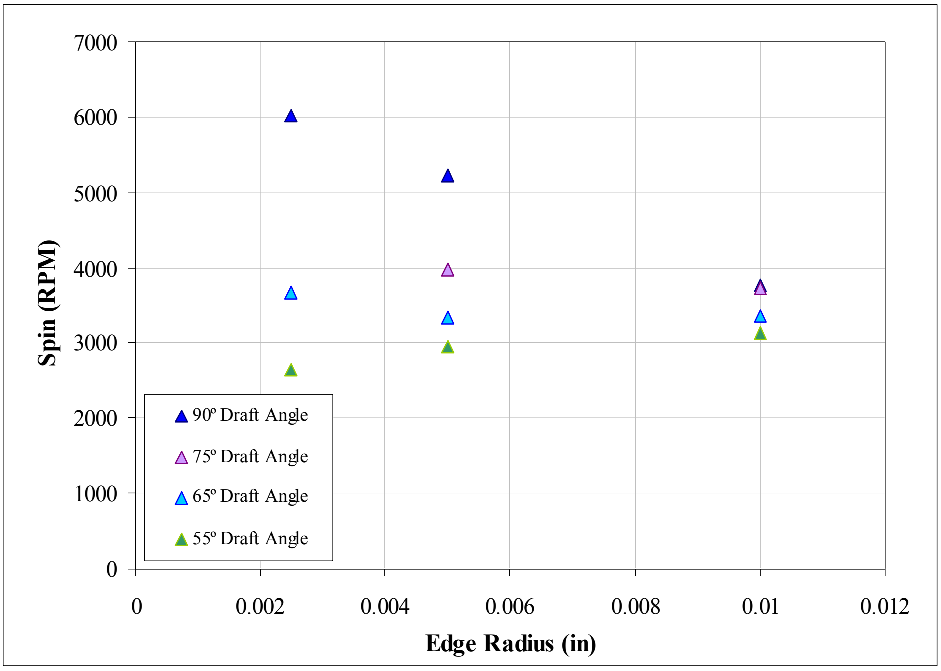


Figure 6.7.1: Three-piece urethane ball (U3P), 35 degree impact

It can be seen that at the largest draught angle of ninety degrees (U-groove), the effect of edge radius on increasing spin is pronounced at all angles. Edge radius also appears to consistently influence spin at a draught angle of seventy five degrees (see Appendix B). However at even lower draught angles, sixty five and fifty five degrees (V-groove), edge radius does not play a significant role in increasing spin.

The results for the four piece urethane covered ball (U4P) are similar to the U3P ball, Figure 6.7.2. (Once again, the results for 35° impact angle are given. Results at other impact angles show similar trends, see Appendix B.) The effect of edge radius on spin is most pronounced for the ninety degree draught angle. For this ball, the edge radius strongly affects the spin at the seventy five degree draught angle as well. As with the U3P ball, the spin at sixty five and fifty five degree draught angles are not appreciably affected by edge radius. It was noted that for this ball, edge radius did not affect the spin appreciably at the highest impact angle, 62 degrees.

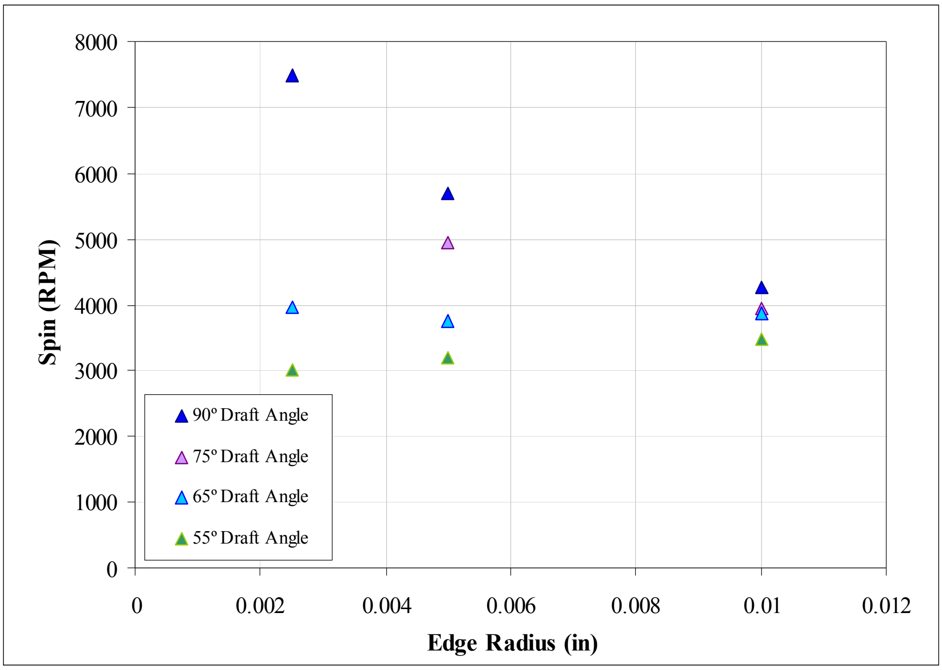


Figure 6.7.2: Four piece urethane ball (U4P), 35 degree impact

The results for the two piece Surlyn cover ball (S2P) are given in Figure 6.7.3 for the 35° impact angle (see Appendix B for results at other angles.) For the Surlyn covered ball neither the edge radius nor the groove shape appears to influence the spin at all.

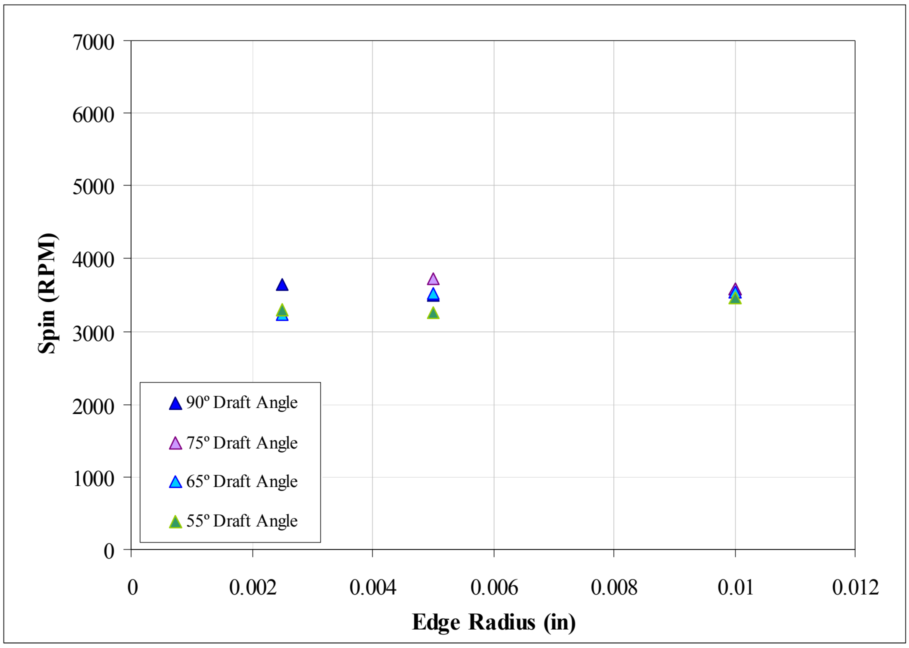


Figure 6.7.3: Two piece Surlyn cover ball (S2P), 35 degree impact

Figures 6.7.4 through 6.7.6 compare the effect of edge radius on the U and V grooves for the three balls tested at 35°.

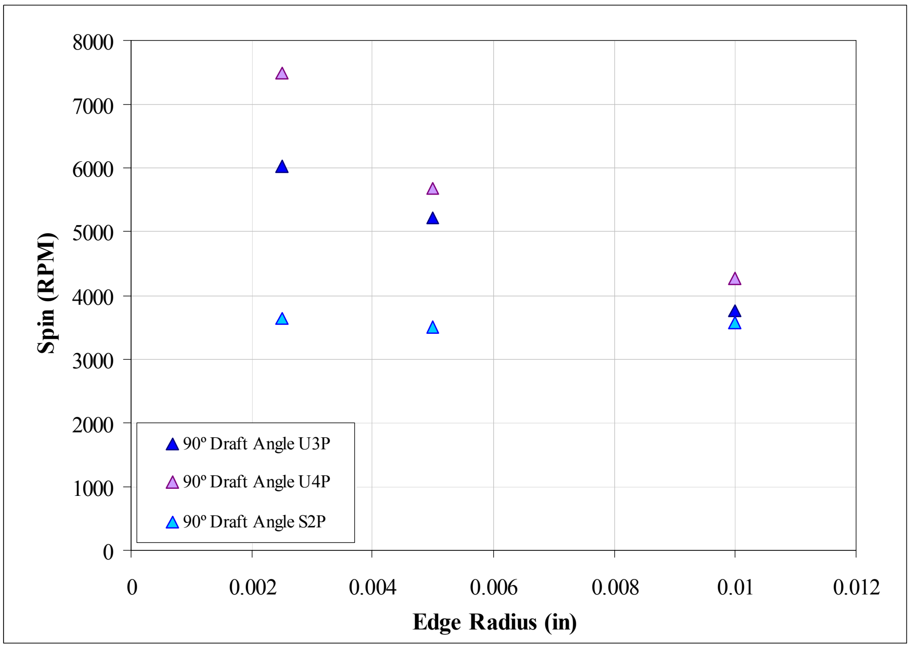


Figure 6.7.4: Comparison of edge radius effects for three ball types (U-groove, 35 degree impact)

It can be seen in Figure 6.7.4 that, for U-grooves (90 degree draught angle) at an edge radius of 0.010-in, the performance of all three ball types are similar. However, at an edge radius of 0.005-in, the urethane covered balls have clearly superior spin over the Surlyn ball. Finally, at the sharpest edge radius (0.0025-in), the four piece urethane cover ball (U4P) outperforms the three-piece urethane cover ball (U3P).

The effect of edge radius at the seventy five degree draught angle is shown in Figure 6.7.5. Again, it may be seen that edge radius affects the ball types differently. It has the greatest effect on U4P less effect on U3P and little or no effect on the S2P Surlyn cover ball.

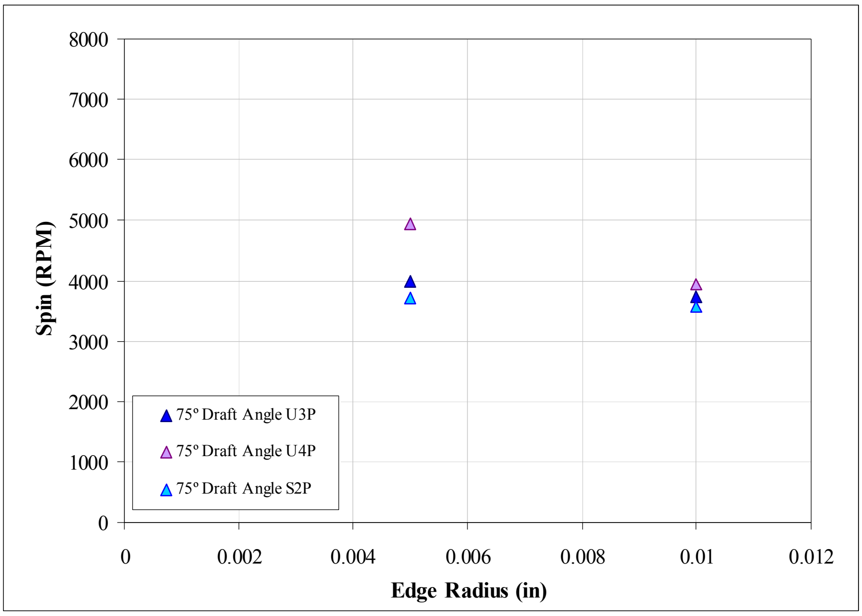


Figure 6.7.5: Comparison of edge radius effects for three ball types (75 degree draught angle, 35 degree impact)

The effect of edge radius on sixty five and fifty five (V-groove) degree draught angles is negligible as can be seen in Figure 6.7.6.

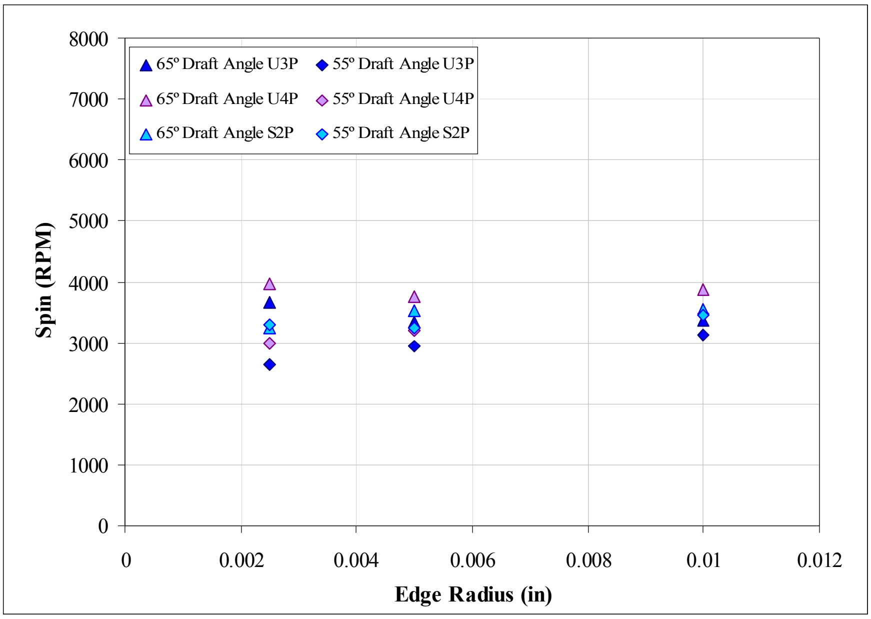


Figure 6.7.6: Comparison of edge radius effects for three ball types (65 and 55 degree draught angles, 35 degree impact)

From these results, it is evident that the effect of edge radius on spin depends on both the shape of the groove and the ball type. Edge radius is most influential for steep groove sidewalls (ninety and seventy five degrees). The edge radius affects the two urethane covered ball types differently. The groove shape and edge radius have little effect on the spin of a two piece Surlyn ball.

These findings demonstrate that, in the absence of control on edge radius, regulations limiting the performance of any groove profile feature (that is depth, width etc.) could be mitigated to some extent by the choice of ball.

6.8. Ball Aerodynamics and Turf Impact

The face treatments on a club affect the launch conditions and thus both the ball flight trajectory and the resulting bounce and roll on the turf. Using the experimentally measured launch conditions from the benchmark testing with U- and V-grooved faces, the aerodynamic coefficients of lift and drag were determined for two types of golf balls over a broad range of speeds and spins. This aerodynamic model was then used to generate turf impact conditions (speed, angle and spin) with which to determine how the ball would bounce and roll on a surface representative of a championship quality green.

6.8.1. Ball Aerodynamics

For several years, golf's ruling bodies have relied on the USGA's Indoor Test Range (ITR), Appendix C, for the determination of aerodynamic characteristics used to simulate golf ball trajectories. However, the system in its current form is limited to those launch conditions associated with the driver. Because of the limitations posed by the ITR an outdoor golf ball tracking system that allows three-dimensional outdoor trajectories to be recorded with a high degree of accuracy was used to estimate aerodynamic coefficients for shots from irons.

The launch conditions derived from the benchmark player testing using V-groove clubs with wound, balata covered golf balls and U-groove clubs with a modern, three-piece, urethane covered ball (U3P) from both fairway (dry) and rough lies were extended to a wider range of lofts, Table 6.8.1.1.

Table 6.8.1.1: Ball Launch Conditions for Aerodynamic Study

Condition	Iron	U3P/ U-Groove			Wound Balata / V-Groove		
		Speed (ft/s)	Angle (°)	Spin (rps)	Speed (ft/s)	Angle (°)	Spin (rps)
Dry	3I	195	15	85	195	12	97
	5I	189	16	88	188	14	110
	7I	179	18	99	176	17	128
	9I	164	21	119	161	20	146
	SW	131	29	168	129	27	177
Rough	3I	186	14	104	188	13	65
	5I	181	14	108	177	16	59
	7I	170	17	109	162	20	54
	9I	155	22	105	147	25	54
	SW	119	35	88	119	34	64

A first-order estimate was then used to develop four trajectories that would envelope the range of Reynolds numbers and spin ratios for which aerodynamic data was desired. Given the range of spin ratios and Reynolds numbers it was decided that the most efficient use of apparatus and manpower would be to use a limited set of initial conditions to span the entire range. From these trajectories, launch conditions were chosen with four spin rates, a fixed initial launch speed (235 ft/s), and a maximum practical launch angle. Balls were then launched outdoors and the trajectories were tracked. For each ball type, and at each of the four launch conditions, twenty trajectories were tracked.

The lift and drag coefficients were determined from the time-dependent positional data of each trajectory. (The method used to derive the aerodynamic coefficients is discussed in detail in Appendix C.) Once the lift and drag coefficients were determined, interpolary fits were used to simulate the full range of iron launch conditions. Simulated trajectories, including landing angle, spin, and carry could then be generated for any iron launch condition.

The launch conditions from the extended benchmark testing, Table 6.8.1.1, were then used to generate simulated trajectories for the two club/ball combinations. Table 6.8.1.2 shows the landing conditions for both club/ball combinations at each of these launch conditions.

Table 6.8.1.2: Ball landing conditions from the simulated trajectories with launch conditions from Table 6.8.1.1

Condition	Iron	U3P/ U-Groove			Wound Balata / V-Groove		
		Speed (ft/s)	Angle (°)	Spin (rps)	Speed (ft/s)	Angle (°)	Spin (rps)
Dry	3I	83	44	71	80	40	82
	5I	82	44	74	78	43	93
	7I	81	46	84	76	46	110
	9I	78	48	103	74	48	128
	SW	72	51	151	68	50	160
Rough	3I	79	43	89	85	35	55
	5I	78	42	93	85	36	50
	7I	78	44	94	85	39	47
	9I	78	46	92	83	43	47
	SW	75	52	80	76	49	58

As indicated in Table 6.8.1.2, the differences between the modern ball/U-groove combination and the wound balata/V-groove combination are exaggerated on shots from the rough. The landing angle difference between the two combinations for launch conditions representing the sand wedge is about one degree in the dry, compared with three degrees in the rough. For the 3-iron the landing angle difference goes from four degrees to eight. Differences in spin on approach correlate roughly to the differences in launch spin in Table 6.8.1.1. Approach speeds for the wound balata/V-groove combinations are notably greater from the rough than the dry, the reverse of the case with the modern ball/U-groove combinations, principally due to the greatly diminished spin-induced drag (for example, using Equation (10) (see Appendix C) and the data from Table 6.8.1.1, it can be shown that the initial drag for wound balata/V-groove 7i-dry is nearly 30% greater than the 7i-rough). These differences in landing conditions have a great effect on how the ball behaves when it impacts the green.

6.8.2. Turf Impact

Once the landing conditions of the ball when launched from various lies with different clubs were known, the goal was to determine how the ball would bounce and roll on a surface representative of a championship quality green.

A series of nineteen test settings were designed to efficiently envelop the landing conditions provided in Table 6.4.1.2. Figure 6.8.2.1 plots the landing conditions and the test settings.

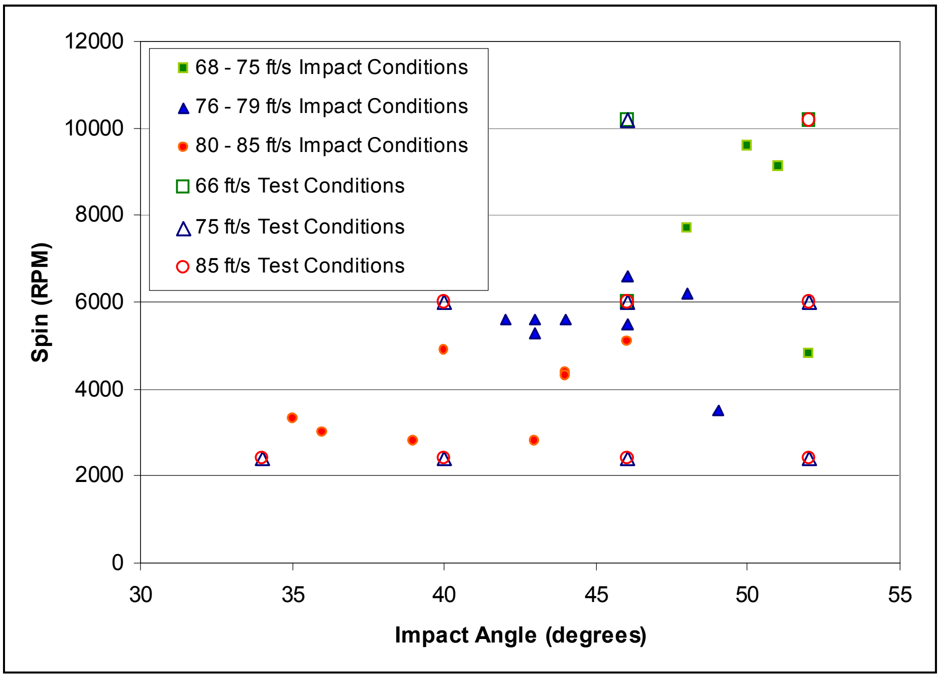


Figure 6.8.2.1: Impact conditions and test settings

A turf nursery, that was constructed and maintained in the same manner as the greens on the course, was used for the testing. A modified pitching machine was used to launch the ball with the desired test settings. High speed video was used to capture the actual impact and rebound conditions (inbound and outbound ball speed, angle and spin). The distance of the first bounce was recorded along with the total distance the ball bounced and rolled. Balls were launched at each condition three times for a total of 57 impacts. (Complete details of the test set-up and procedure are given in Appendix D.)

The ball conditions (speed, angle and spin) that were measured immediately after the initial impact were compared to the three inbound conditions. It was found that the outbound ball speed and angle were mainly a function of the inbound angle. The outbound spin rate was mainly influenced by the inbound spin rate. These results are plotted in Figures 6.8.2.2, 6.8.2.3 and 6.8.2.4.

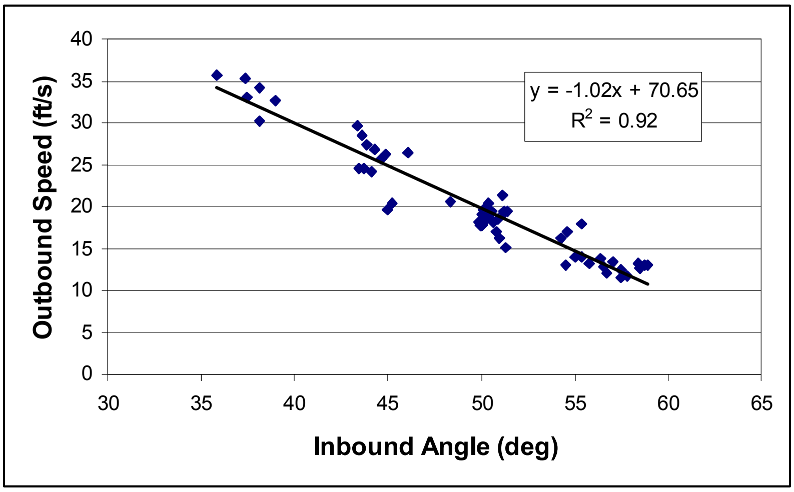


Figure 6.8.2.2: Rebound ball speed

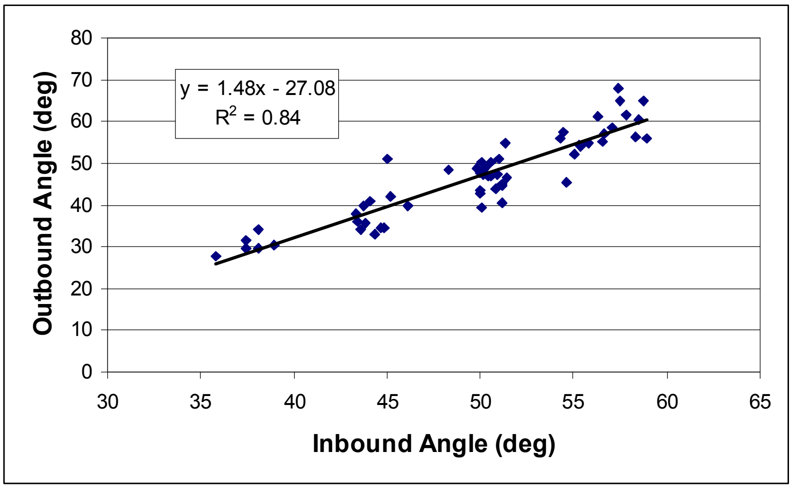


Figure 6.8.2.3: Rebound angle

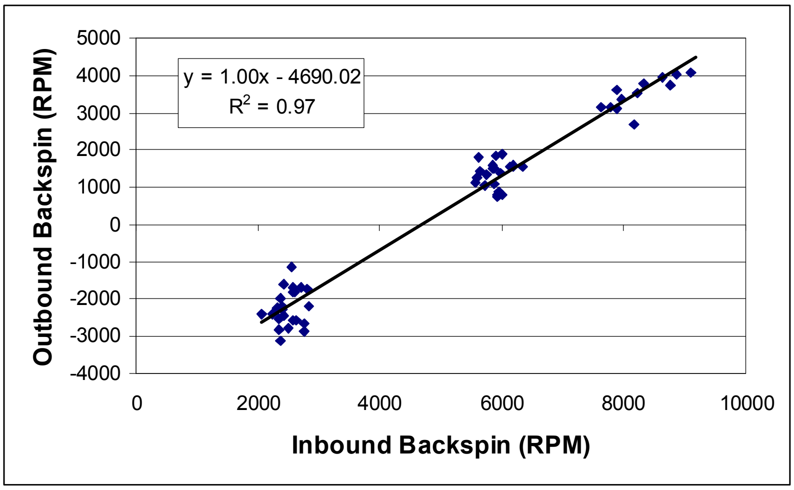


Figure 6.8.2.4: Rebound spin rate

The total bounce and roll of the golf ball after the initial impact is strongly a function of the inbound angle and the inbound spin, therefore a linear regression equation of the total bounce and roll (in feet) as a function of inbound angle and spin could be developed. Predictions of the total roll using this equation agreed very well with the measured roll values (R^2=90%) (The derivation of this equation is discussed in detail in Appendix D.)

This equation was then used to determine differences in bounce and roll performance using the actual launch conditions measured from the benchmark player testing for the 5-iron, 8-iron and sand wedge for the two club/ball combinations (wound balata/V-groove and modern multi-layer urethane/U-groove) from the fairway and the rough. The resulting total bounce and roll for these two ball/groove configurations is plotted in Figure 6.8.3.5. Also shown is the estimated bounce and roll for the modern ball from the fairway. It should be noted that these estimates are for a flat green.

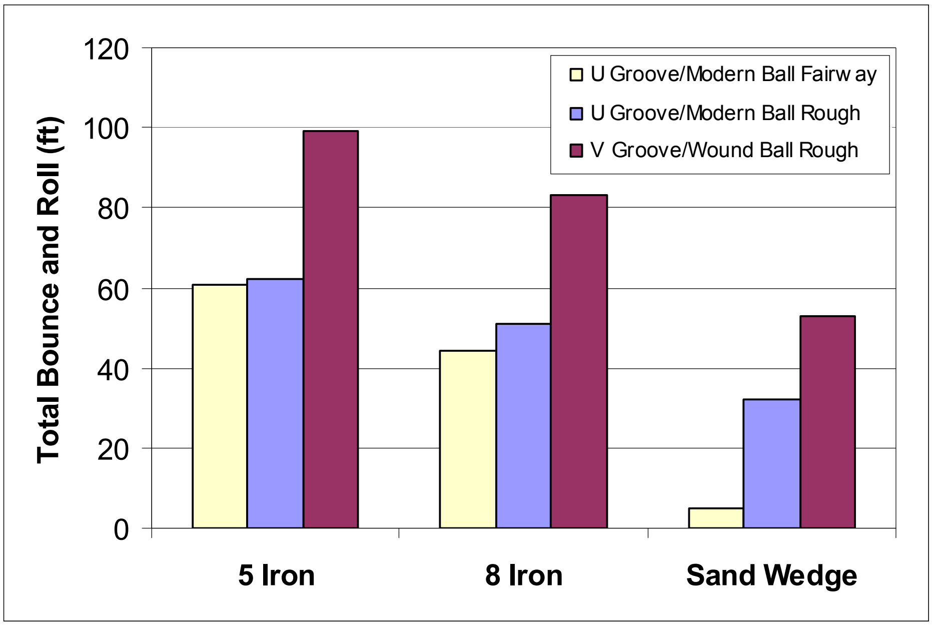


Figure 6.8.3.5: Effect of groove and lie on total bounce and roll

The landing conditions for shots from the rough with the wound balata/V-groove had significantly shallower inbound angle and lower spin rates than the modern ball/U-groove combination. This lead to significantly longer total bounce and roll for the V-groove compared to the U-groove. The total bounce and roll of the wound balata/V-groove combination from the rough was approximately 60% higher than the modern ball/U-groove combination and, for the 5- and 8-irons, the modern ball/U-groove combination the bounce and roll from the rough is nearly identical to that from the fairway.

7. Player Testing

From the laboratory testing a set of modified groove specifications was developed for groove profiles that were not V-shaped but would produce spin performance similar to that of a traditional V-groove in grassy lies. The objective of this subsequent player testing was to verify the laboratory tests on the Phase I and Phase II plates and to demonstrate that equipment manufactured with modified face treatment specifications would exhibit the same effects when used by golfers in shots from light rough.

7.1. Tour Player Testing

The tour player testing was conducted in two phases. The first phase used a large selection of clubs designed with groove profiles that were not V-shaped yet performed like V-grooves in addition to the U and V groove sets. These clubs were tested by players from a professional golf developmental tour. Based on the results of this first phase of player testing, a smaller subset of the modified groove profiles was selected for a second phase of player testing with PGA Tour players. In both phases the launch conditions, measured by a radar tracking unit, were obtained from fairway lies and in the light rough.

Eight sets of clubs were assembled with unique groove configurations. Each set of clubs used in the player testing contained a 5 iron, an 8 iron and a sand wedge. With the exception of sets that were U-grooves and V-grooves at current conformance limits, all of the groove configurations chosen exhibited performance similar to that of the V-groove in the laboratory testing with a grass surrogate. Table 7.1.1 lists the groove configurations for which club sets were manufactured. (A complete description of the player tests, including drawings of the groove profiles of the clubs used, is given in Appendix E.). All tests used a modern, urethane cover, three-piece ball (U3P).

Table 7.1.1 – Test Club Groove Specifications

Set ID	Groove ID	Edge Radius (in)	Groove Spacing* (in)	Groove Width** (in)	Groove Depth (in)
A	U (R402)	0.005	0.14	0.03	0.02
B	V (B402)	0.005	0.14	0.03	0.02
C	WD101	0.01	0.14	0.0225	0.015
D	RWD101	0.005	0.14	0.023	0.014
E	RWD102	0.0025	0.14	0.02	0.01
F	WS101	0.01	0.175	0.0225	0.02
G	VRS123	0.005	0.175	0.03	0.0148
H	VRS101	0.0025	0.245	0.0219	0.02

* Groove Spacing is centreline to centreline
** Groove Width using 45° method

7.1.1. Developmental Tour Player Testing

The first phase of the player testing was performed by six professional golfers currently competing on a developmental tour. Each player was asked to hit shots using each loft of the

U-groove and V-groove sets from light rough (they were also asked to hit the U-groove clubs from a fairway lie.) They were then asked to hit shots using each loft of two of the sets of V-like groove sets from light rough. Using this approach, each of the V-like groove sets, C through F, were tested by four players. Players were not made aware of the groove designs prior to testing.

For each shot, radar was used to track the launch and the resulting trajectory, and high speed video was used to capture the incoming club trajectory and the initial ball launch. The results of the individual player tests for the various groove configurations were grouped and are presented in Figure 7.1.1.1

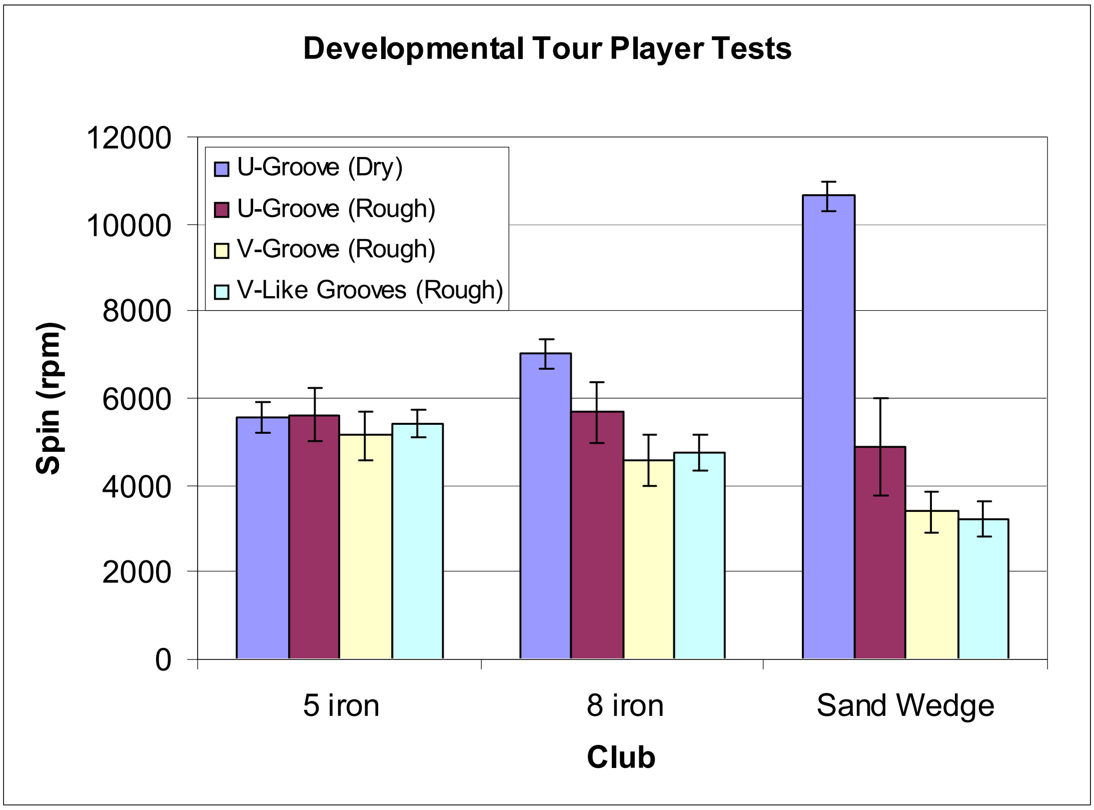


Figure 7.1.1.1: Developmental Tour Player Test Results

From the data it can be observed that for both the 8 iron and the SW, the spin produced by the V-like groove clubs was very similar to the V-groove and different from the U-groove. Data for the 5 iron showed less discernable differences between the various groove configurations.

7.1.2. PGA Tour Player Testing

The second phase of the player testing was performed by nine professional golfers from the PGA Tour. For the PGA Tour player testing, the number of V-like groove configurations was pared down to only the C and F configurations listed in Table 7.1.1. This phase of the testing was conducted at two different venues, both of which had turf grass that was more similar in structure to the grass at the venue where the benchmark player testing was conducted.

Players were asked to hit shots using a particular club loft of U-groove and V-groove club sets from light rough (they were also asked to hit the U-groove clubs from a dry lie.) They were then asked to hit shots using the same loft of the two selected V-like groove clubs (sets C and F in Table 7.1.1) from light rough. When possible, the player repeated the procedure with a second loft. Using this approach each loft of each groove configuration was tested by four players. Once again, radar was used to track the launch and the resulting trajectory, and high speed video was used to capture the incoming club trajectory and the initial ball launch.

Like the developmental tour player testing, the individual player test results were grouped. The averaged results for the nine PGA Tour players are shown in Figure 7.1.2.1.

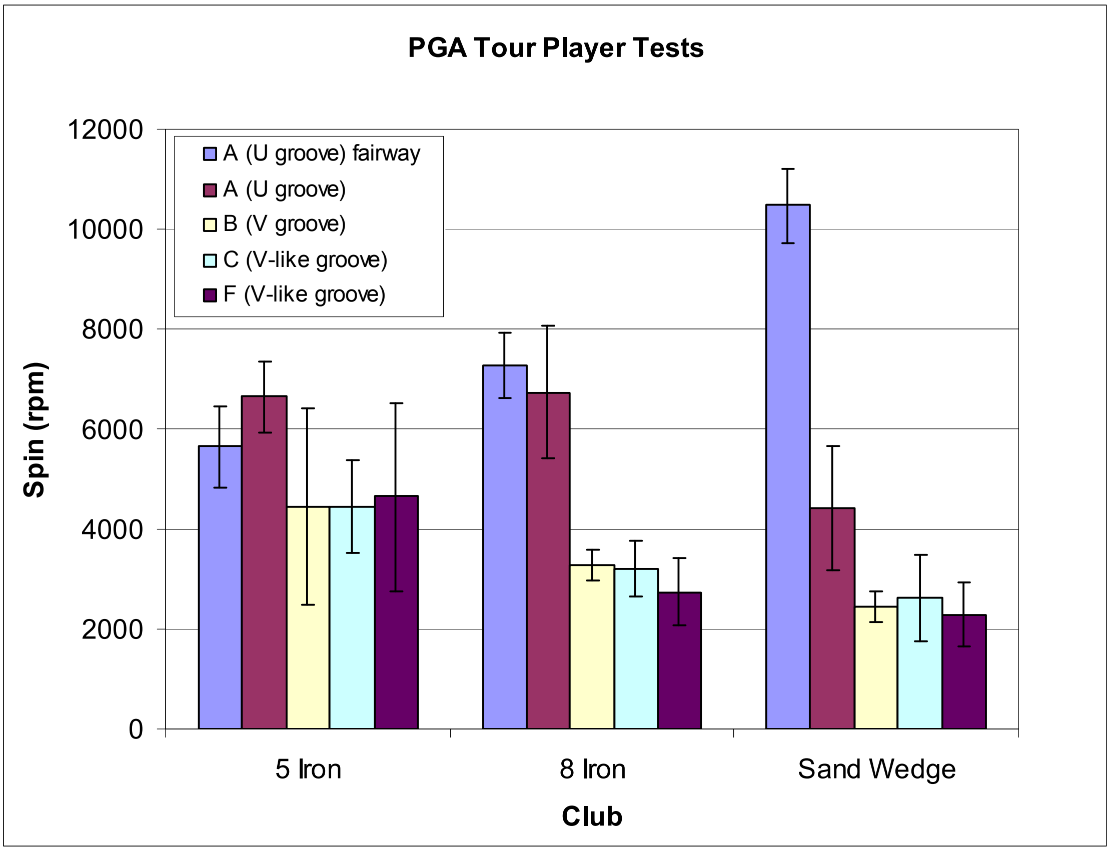


Figure 7.1.2.1 – PGA Tour Player Test Results

From Figure 7.1.2.1 it can be observed that, for all lofts, the V-like groove clubs performed very similarly to the V-grooves and differently from the U-grooves. It can also be observed that the confidence intervals of the data (compared as a percentage of the mean spin) for the U-groove, V-groove and V-like groove configurations in the rough were similar; approximately +/- 22% on average. This is about approximately double the confidence interval for the dry configuration and indicates that shot variability between the different groove configurations is comparable.

7.1.3. Comparisons of Tour Player Tests

The overall trends in both the developmental tour and PGA Tour player test results were also consistent with the lab tests and the benchmark player tests. The dry spin increased from the 5-iron through the sand wedge; the U-groove showed similar spins from the rough at both the 5-iron and 8-iron lofts, and a decreased spin rate with the sand wedge; and the V-groove (and V-like grooves) exhibited less spin than the U-groove at all lofts.

Whilst the results of the various player tests (benchmark, developmental tour and PGA Tour) were similar, they were not identical. For instance, there was a difference in the relative spins of the U-groove for 8-iron in the dry and wet conditions in the developmental tour player test data that was not evident in the benchmark or PGA Tour player test data. The benchmark player and PGA Tour player test data showed no significant difference in the shots from dry and wet lies with the U-grooved 8-iron, whilst there was a statistically significant drop in spin with the same club in the dry and wet conditions for the developmental tour tests.

Like the developmental tour and PGA Tour player testing, during the benchmark testing the individual player test results were grouped. During the benchmark testing three of the six players showed a slight increase in spin between the dry and wet conditions with the U-groove 8-iron whilst the other three players showed a slight decrease in spin between the dry and wet conditions. So it is not unreasonable that, given a finite number of test subjects, the mean spin in the dry may be significantly different from the rough for the eight iron. Yet despite the difference between the wet and dry spin data for the U-groove 8-iron in the developmental tour player testing, when the data from the developmental tour and benchmark venues are compared, there was no statistical difference in the spin performance of U-groove 8-iron between the two tests, in either the wet or dry condition. Figure 7.1.3.1 is a side by side comparison the results of the U-groove 8-iron from these two tests.

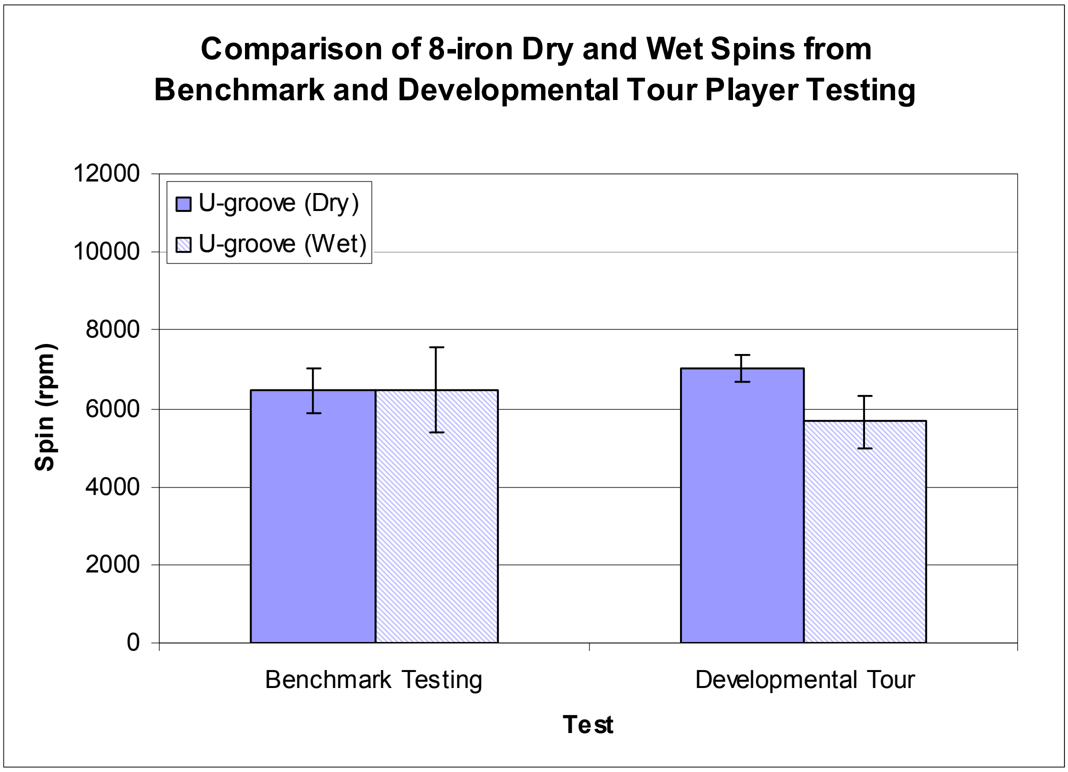


Figure 7.1.3.1 – Comparison of Benchmark and Developmental Tour Player Test Results for the U-groove 8-iron

Also, the differences in the spins between the U-groove and V-groove clubs (for the wet condition) in developmental tour player test data were not as pronounced as they were in the benchmark player test data. Unsurprisingly, this indicates that the quantitative (but not qualitative) performance of the various groove shapes has some dependence on the type of grass in the rough. Whilst the rough at the venues of both the benchmark and developmental tour player testing was Bermudagrass; the area of the course where the benchmark testing was conducted used a growth regulator. The use of this growth regulator leads to a more leafy plant with fewer and shorter stems. This contrasts with the testing area used for the developmental tour where no growth regulator was used; creating a less leafy plant with more and taller stems. Recognition that the performance of all shots from the rough are in some fashion dependent on the grass was part of the rationale for choosing two grass surrogate materials for the laboratory testing.

7.1.4. Tour Player Test Conclusions

The results of the player tests confirm the effects that the modified face treatment had on spin that were demonstrated in the laboratory tests. Furthermore it was demonstrated that it was possible to manufacture club faces with groove profiles that were not V-shaped yet performed like V-groove clubs when used by golf tour professionals in lies in the light rough.

7.2. Amateur Player Testing

Player testing was also conducted with amateur golfers to determine the effect that clubs with modified face treatment would have on golfers of average skill levels. The first part of the amateur player testing was similar to the Phase II, PGA Tour player testing, where golfers were asked to hit shots using different club lofts of U-groove and V-groove clubs from light rough.

The second part of the amateur player testing was an on-course study whose objective was to quantify the percentage of shots that amateur golfers were able to hit from various distances and lie conditions and which staid on the green.

7.2.1. Spin Testing

The launch conditions of fifteen different amateur golfers with handicap indices that were uniformly distributed over a range from 1.9 to 19.8 were measured. Like the tour player testing, the launch conditions of the golfers were measured using a radar system as the golfers hit shots using different club lofts of U-groove and V-groove clubs from light rough.

The testing was divided into two portions; one evaluating the effect of groove geometry on spin, and the second evaluating the effect of the ball cover material on spin. Two sets of irons were used in the testing; one U-groove design representing the limit of conformance, and the other representing a full dimension V-groove. The two balls used in the testing were a Surlyn covered two-piece "distance" ball (S2P) and a three-piece urethane covered ball (U3P) that was used in the laboratory and previous player tests. All shots were hit from lies in the light rough. Complete details of the test and results are included in Appendix F.

The first round of testing was conducted with 11 players, four irons, and the urethane covered ball. The irons used in this test were 8 irons with a U-groove and a V-groove, and 5 irons with a U-groove and V-groove with each player hitting a total of 40 shots.

Figure 7.2.1.1 shows the results of this test for the U- and V-groove 8 irons. All eleven subjects had a mean spin value for the U-groove 8 iron that was higher than that of the V-groove 8 iron. Ten of the eleven subjects had statistically significant differences in spin between the U- and the V-grooved 8 irons. There was also a weak correlation between handicap and standard deviation. Unsurprisingly, it was observed that there was a tendency for the lower handicap subjects to have lower variability.

Similar trends were observed in the test for the U- and V-groove 5-irons where, for 10 of the 11 subjects, the mean spin value for U-groove 5 iron had more spin than the V-groove 5 iron. Six of the subjects, primarily those with the lowest handicaps, had a statistically significant difference between the spin of the U- and V-groove clubs.

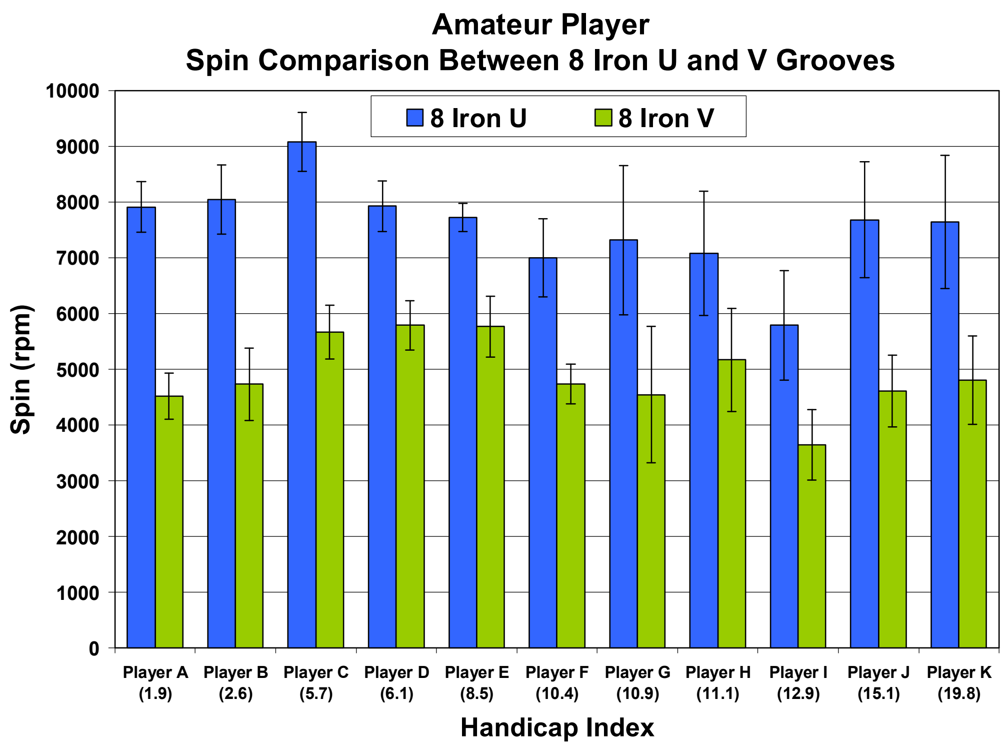


Figure 7.2.1.1 - Comparison of Amateur Player Launch Spin for U-and V-Groove 8-Irons.

When the data is combined for all players there is a statistically significant difference in the means for the spin values for the U- and V-groove clubs for both the 5 and 8 irons. At both lofts the U-groove had higher spin than the V-groove, Figure 7.2.1.2.

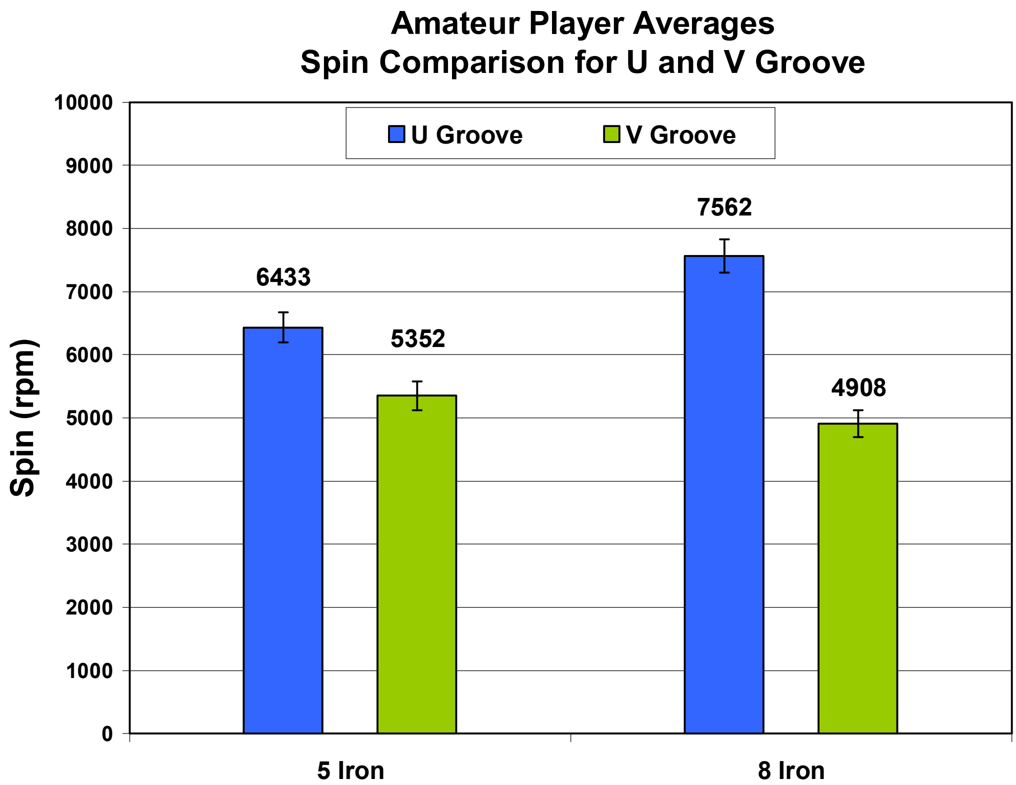


Figure 7.2.1.2 Comparisons of player average launch spins.

The second segment of the testing involved 6 subjects using only the U- and V-groove 8 irons with two ball constructions. The testing was conducted in a similar manner as the previous tests but with each subject hitting both urethane and Surlyn covered balls to ensure that the groove dependency with urethane that was seen with previous tests was still exhibited by the subjects in these tests.

The spin results for the four combinations tested are shown in Figure 7.2.1.3. Each player in this series of tests again had higher mean spin values for the U-groove over the V-groove with urethane covered balls, and each showed a statistically significant difference between the U-groove and V-groove. However, for the Surlyn covered balls, there was no significant difference between the U- and V-grooved clubs. Although most of the subjects did demonstrate a slight decrease in spin from the U-groove to the V-groove, only one subject showed a statistically significant decrease. Furthermore none of the differences were nearly as large as were observed with urethane covered balls. In fact, the spin rates of both the U and V groove tests with Surlyn were not statistically different from the spin values obtained with the V-groove urethane combination.

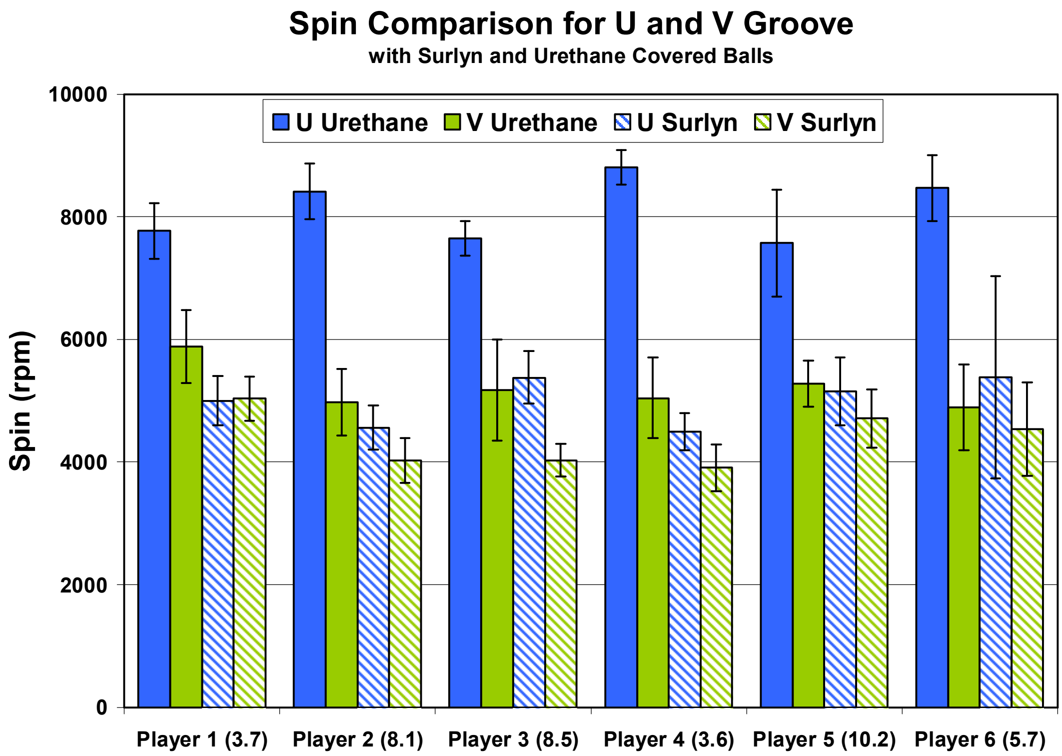


Figure 7.2.1.3 - Spin comparison for amateurs with urethane and Surlyn covered balls (8-Iron).

The test results demonstrated that, like the professional golfers, there is an appreciable difference in spin rate achieved with amateur players using U-grooved clubs with urethane covered balls over spin rates with V-grooved clubs. The U-groove club and urethane covered ball combination consistently achieved higher spin rates, and this was most apparent at the 8 iron loft. However, there is only minimal difference in spin rates achieved by amateur golfers when using U- and V-grooved clubs in combination with Surlyn covered balls. This type of ball makes up approximately 70% of the golf balls sold at on and off-course retailers (with the US)[2]. These tests also demonstrate that the spin performance of a urethane covered ball in concert with a V-groove has very little advantage over a Surlyn covered ball and either groove configuration.

7.2.2. Shot Dispersion

Measurement of amateur golfer shot dispersion was conducted over two days at the Walt Disney World Resort's Palm and Eagle Pines golf courses. Eight hundred and twenty four data points from four hundred and twelve shots were taken. The locations of the approach shot and the final position of the ball in the area of the target green were measured. All of the measured shots occurred during normal stipulated rounds of golf.

Three holes, all four pars, were used in the study. One hole was 385 yards long and had a green area of 750 square yards. The second was 367 yards long with a green area of 440 square yards and the third hole chosen had a length of 351 yard with a green area of 375 square yards. (An average green has an area of about 550 to 600 square yards.) The fairway widths ranged from 28 to 38 yards wide at a distance of 100 to 175 yards out from the hole and the rough was a 1.0 to 1.75-in high Bermudagrass. Complete details of the amateur player dispersion testing are given in Appendix G.

Table 7.2.2.1 is a summary of the dispersion data collected for the three holes used in this study. Of the 412 approach shots measured, 217 were from the rough. The percentage of shots that finished on the green when hit from the rough varied for each hole and was dependent on range from hole as well the gross area of the green.

Table 7.2.2.1 - Summary of Amateur Dispersion Data for the 412 Measured Shots.

	Lie	Hole 1	Hole 2	Hole 5	Overall	PGA Tour*
Approach Location (# of shots)	Fairway	43	51	74	168	98813
	Rough	50	54	113	217	50840
	Bunker	4	13	9	26	
Percentage On Green	Fairway	21%	10%	25%	19.4%	75%
	Rough	4%	5%	21%	13.1 %	49%**
	Bunker	0%	7%	0%	3.8%	
Green Area		440 sq. yd.	375 sq. yd.	750 sq. yd.		

* 2006 PGA Tour data (par 4 holes only)

** Includes all non-fairway approach shots.

As highlighted earlier, the greens on two of the holes chosen had roughly half the area of the green on the third hole. This was likely a contributing factor to a substantial difference in the percentage of shots from the rough finishing on the green, 4-5% vs. 21%. This large difference between the percentages of shots finishing on the green was less pronounced for the shots hit from the fairway for the two courses, 10-21% vs. 25%. Overall 13.1% of the approach shots measured finished on the green.

Figures 7.2.2.1 is a sample scatter plot of all of the shots measured on one of the holes. (Scatter plots for the other holes are included in Appendix F.) Each red point represents the starting location of a single approach shot, whilst there is a corresponding single yellow point representing the final location of that approach shot. These scatter plots have been superimposed over an artist's rendition of the hole

In order to analyse these three data sets in a more cohesive manner, the three data sets were combined by superimposing the centres of the greens at the origin and rotating each set of data such that 150 yard markers were all in alignment. The data was then quantified in terms of radial distance from the hole as opposed to the binary information of being on or off of the green.

Figure 7.2.2.2 is a histogram displaying the percentages of approach shots from the rough that finish within 5 yard concentric rings from the hole. (An equivalent chart of shots from the fairway is included in Appendix F.) For shots from both the fairway and rough, approximately 14% finish between 20 and 25 yards from the hole. Superimposed on the histogram in red is a curve representing the cumulative percentage of shots within a given radial distance from the hole. The data indicates that approximately 95% of all of the approach shots from the fairway and rough finish within 100 yards of the hole. The 50% cut off does, however, vary for the two lies. Fifty percent of all of the approach shots from the rough finish within 30 yards of the hole, where from the fairway, nearly 60% of the shots are within 30 yards of the hole. In order to see the actual percentage of shots that were on the green, the bars of the histogram were coloured green. The data also showed that the longer the approach shot, the further away from the hole the approach shot finished.

Figure 7.2.2.1 – Sample Amateur Shot Distribution

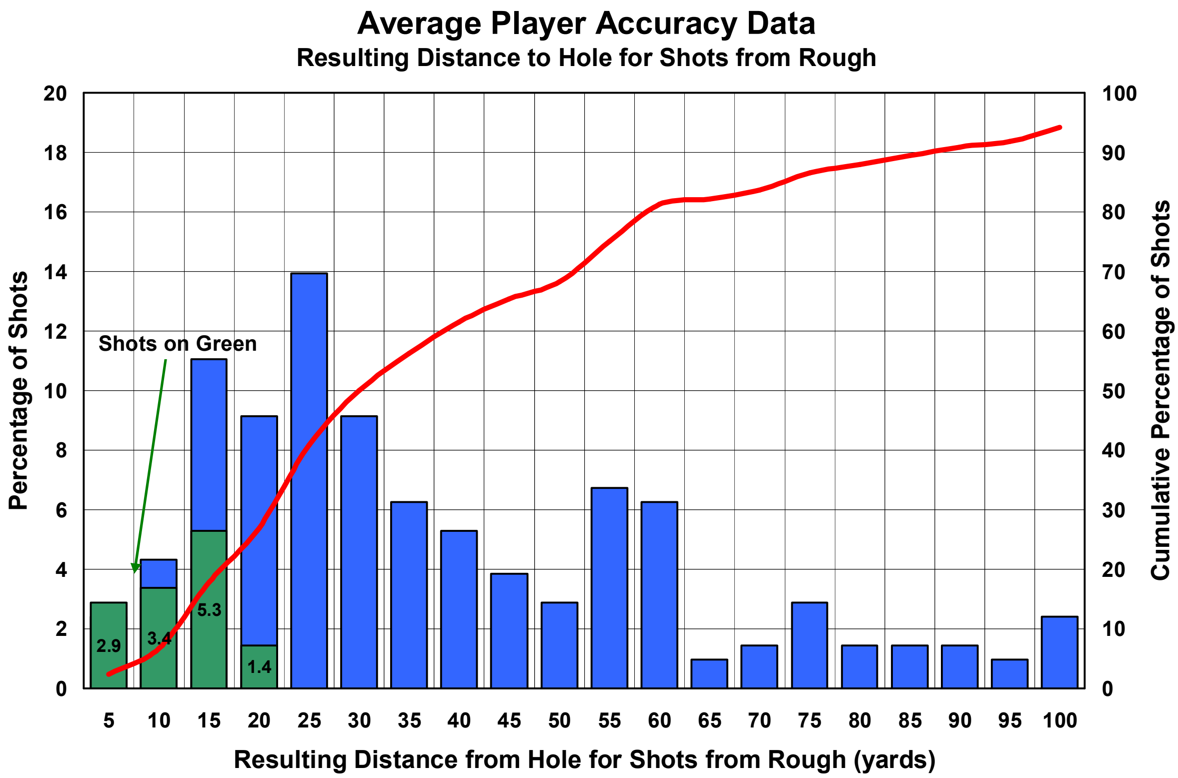


Figure 7.2.2.2 - Amateur player accuracy data for shots from the rough

The results show that for approach shots from within 100 yards out to just beyond 200 yards, 13.1 percent of the time this population of amateur players successfully kept the ball on the green for shots from the rough. Unsurprisingly, as the area of the green decreases, the percentage of shots on average that finish on the green does also. And of those that do finish on the green their distance from the hole increases with the length of the approach shot.

7.2.3. Summary of Amateur Player Testing

Testing of amateur golfers demonstrated that whilst there is a measurable difference in spin rate between U-grooved clubs with urethane covered balls over spin rates with V-grooved clubs, there is only minimal difference in spin rates achieved by amateur golfers when using U- and V-grooved clubs in combination with Surlyn covered balls, which make up approximately 70% of the golf balls sold by on- and off-course retailers (within the US). Regardless of the ball type, the amateur player selects, tests showed that, on shots from the rough, the average player hits the ball onto the green only a small percentage of the time.

8. Conclusions

Initial testing confirmed that modern groove and face treatment specifications represent a significant performance improvement over more traditional V-shaped grooves.

Laboratory tests were conducted on more than one hundred grooved test plates using grass surrogates as the interface material between the club and ball. These tests showed that:

- The spin increases as the groove profile changes from V to U.
- Decreasing edge radius increases spin. The edge radius effect is greater for large draught angles, however increasing edge radius above 0.010-in has limited effect.
- Decreasing the groove spacing increases spin
- Increasing the groove depth increases spin
- Increasing the groove width increases spin
- Considering only edge radii equal to or greater than 0.010-in the spin performance can be expressed as a function of the cross-sectional area of the groove divided by the groove spacing (pitch).

These face treatments affect the launch conditions and thus both the ball flight trajectory and the resulting bounce and roll of the ball upon impact with the turf. The landing conditions for shots from the rough with the wound balata/V-groove had significantly shallower inbound angle and lower spin rates than the modern ball/U-groove combination. This lead to a total bounce and roll that was approximately 60% higher for the V-groove compared to the U-groove.

Testing of professional golfers tests confirmed the effects that modified face treatment had on spin that were demonstrated in the laboratory tests. Furthermore they demonstrated that it was possible to manufacture club faces with groove profiles that were not V-shaped yet performed like V-groove clubs when used by golf tour professionals in lies in the light rough.

Like the professional golfers, testing of amateur golfers demonstrated a measurable difference in spin rate between U-grooved clubs with urethane covered balls over spin rates with V-grooved clubs. However, there is only minimal difference in spin rates achieved by amateur golfers when using U- and V-grooved clubs in combination with Surlyn covered balls, which make up approximately 70% of the golf balls sold by on- and off-course retailers. Regardless of the ball type that the amateur player selects, tests showed that, on shots from the rough, the average player hits the ball onto the green only a small percentage of the time.

REFERENCES

1. Interim Report on Study of Spin Generation, August 7, 2006.

2. Golf Ball Sales; On-Off Course Shops, April – June 2006, Golf DataTech.

APPENDIX A

OBLIQUE IMPACT TESTING OF GROOVED PLATES

Dec 7, 2006

1. SUMMARY

Two sets of grooved test plates were fabricated and tested for their performance with oblique impacts with golf balls. Two interfacial materials were used to simulate the effect of grass on the impact. The first set of plates (Phase I) was designed to vary individual groove design parameters independently. These parameters were groove shape, width, depth, edge sharpness and spacing. Testing of these plates revealed that the total cross-sectional area of the grooves in the impact area (controlled by groove shape, width, depth and spacing) had a direct affect on the resulting spin. Additionally, it was found that the sharpness of the grooves had a large effect when the groove sidewalls were steep. The effect of edge radius diminished as the groove shape transitioned towards a V-groove profile.

The second set of test plates (Phase II) were designed to have the oblique impact performance of the V-groove but without necessarily having a V-groove profile. Groove design parameters were varied simultaneously to achieve this objective. It was found that the expected performance was slightly lower than that of the V-groove based on findings of the Phase I testing. Results from both sets of tests were then combined and it was found that, for plates having an edge radius of 0.010–in or larger, the spin may be estimated from the total cross-sectional area in the impact zone.

2. TEST METHODOLOGY

A collection of test plates were fabricated, each having a set of grooves with a unique profile and spacing (or pitch). These plates were fabricated using the wire EDM technique to quickly and efficiently produce the groove profiles. Each plate was produced to be mounted to a three axis force transducer using a standardised bolt pattern. The force transducer was mounted to a massive steel block which in turn is clamped to a universal box table. Balls are fired at prescribed velocities against the test plate. The machinist's table pivots such that the impact angle can be varied. Launch monitors are used to record the ball speed, spin and angle of the inbound and rebound ball flight. Figure 2.1 shows the test setup.

Each plate is tested at a range of angles, from 25 to 62 degrees, permitting the response of a full range of iron lofts to be tested. The impact speed is commensurate with the impact angle, that is, the lower the loft, the higher the impact speed. The test protocol[1] describes in detail the impact speed selection and the test settings. Each plate was tested using a urethane cover, three-piece ball. Two interfacial media, selected as surrogates for grass were used for all plates[2].

The plate designs may be separated into two groups. In Phase I, the plates were comprised of four basic groove shapes, a true U-groove (90 degree sidewalls), a semi U- groove (75 degrees), a semi V-groove (65 degrees) and a true V-groove (55 degrees). The groove specification parameters (width, depth, edge radius and spacing) were independently varied.

Figure 2.1: Experimental test apparatus

The Phase II plates were designed, using information gathered in Phase I, to have spin performance similar to that of the V-groove but without necessarily having the profile of a V-groove. Groove design parameters were varied simultaneously to achieve this objective.

3. Theory

The fundamental dynamics of golf ball oblique impact have been investigated in two previous reports[3,4]. However, it is useful to provide a few key findings of these reports here since they may be counterintuitive.

It has been shown that the flexibility of the ball in the tangential direction is very important in understanding the nature of an oblique impact. This flexibility means that over the course of the impact, the tangential force on the ball can first contribute to a tangential impulse and then reduce the impulse before the end of impact. The total impulse imparted to the ball in the tangential direction (the direction that contributes to spin) therefore, can be higher or lower than that predicted using a simple rigid body. Figure 3.1 shows the tangential force time history on a flexible ball compared to an idealised, rigid body sphere.

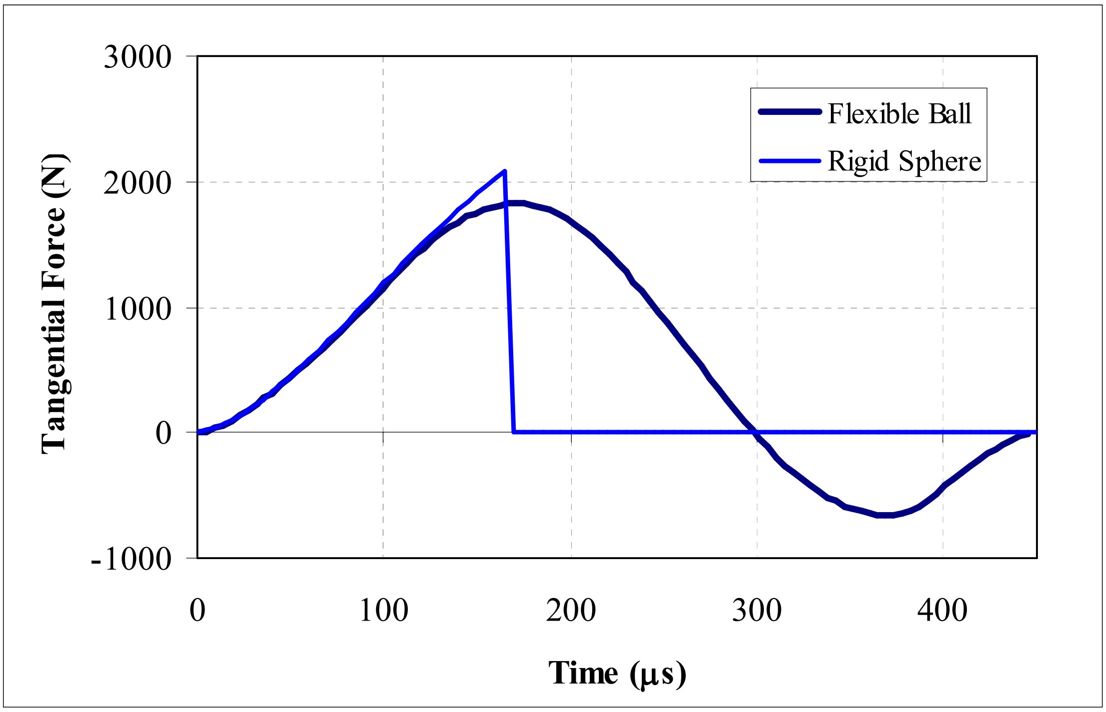


Figure 3.1: Tangential force time history in oblique impact (rigid and flexible balls)

The amplitude and frequency of the tangential force time history will be affected by the (i) the properties of the ball and (ii) the available friction force. The available friction force is in turn affected by the friction of the contact and the angle of the oblique impact. At low angles even low friction surfaces have substantial available high friction force, due to the high normal force. Conversely, even with high friction surfaces, the available friction force is low for high angles due to low normal contact forces.

The effect of the available friction on the response of a typical golf ball is shown in Figure 3.2. Included in Figure 3.2 is the spin predicted by a kinematic consideration of a rigid sphere with infinitely high friction.

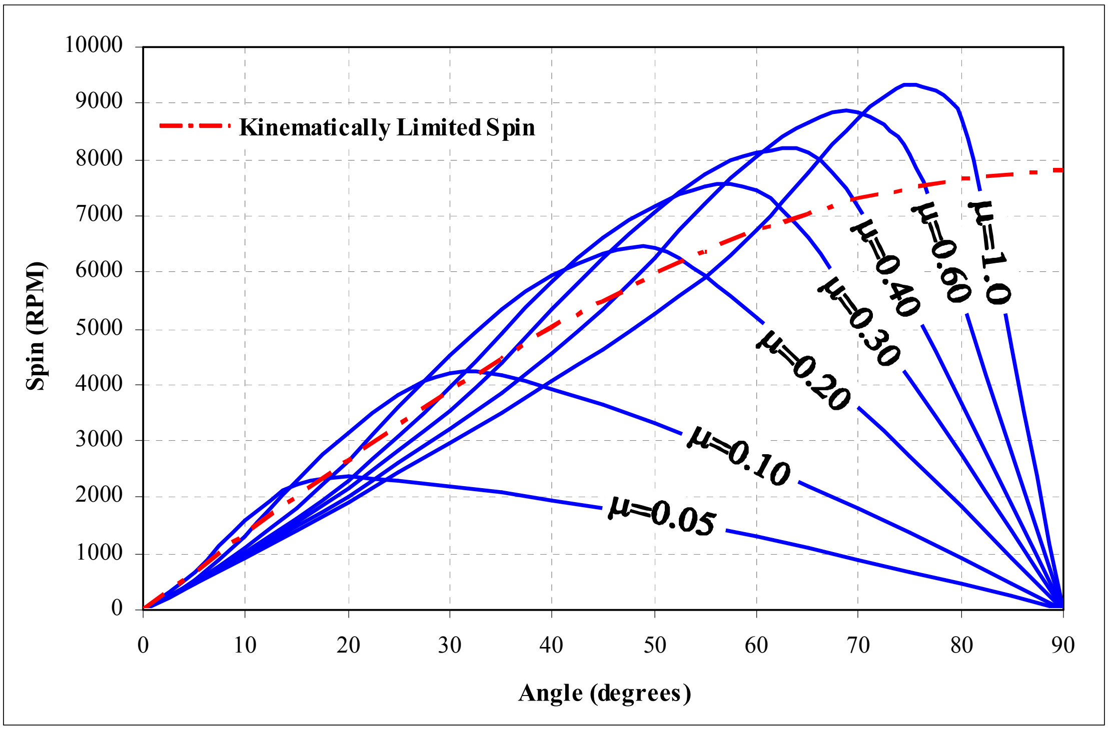


Figure 3.2: Tangential force time history in oblique impact (rigid and flexible balls)

Two important observations can be made from Figure 3.2. First, there is an angle of maximum spin for each coefficient of friction. Increasing the loft beyond this point reduces spin. Next, at a given angle of impact, there is a coefficient of friction that maximises spin. For example, at 40 degrees, it can be seen that the spin for μ=0.20 (approximately 6000 RPM) is substantially higher than μ=0.10 and μ=1.0 (both approximately 4000 RPM). Therefore, increasing friction does not necessarily increase spin.

The observations on the effect of impact angle and friction are important to (i) properly design oblique impact experiments and (ii) interpret the results. Figures 3.3 and 3.4 show experimental results with the newsprint and DuPont Sontara interface materials (acting as surrogate materials for grass). The experimental data are superimposed upon the analytical model results. Results of tests with a clean dry plate are also provided as a reference.

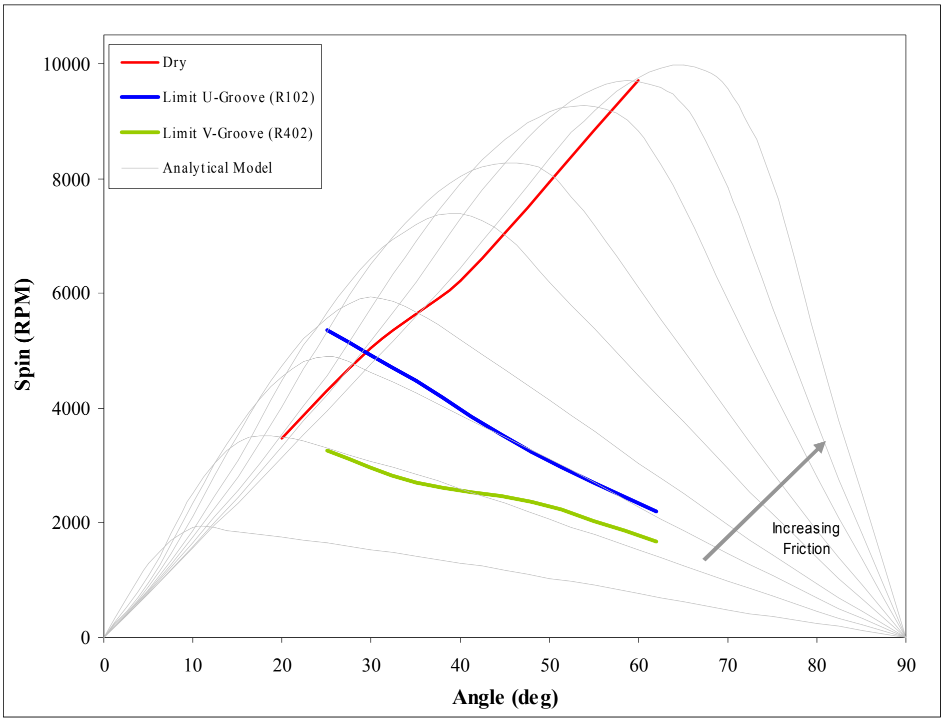


Figure 3.3: Comparison of experimental data and analytical model (wet newsprint interface, U and V groove plates)

It can be seen in Figure 3.3 that the spin consistently decreases with the newsprint interface as the impact angle increases. Again, this may be counterintuitive but agrees well with the model. The concept of the optimum impact angle to maximise spin is demonstrated well using the Sontara material.

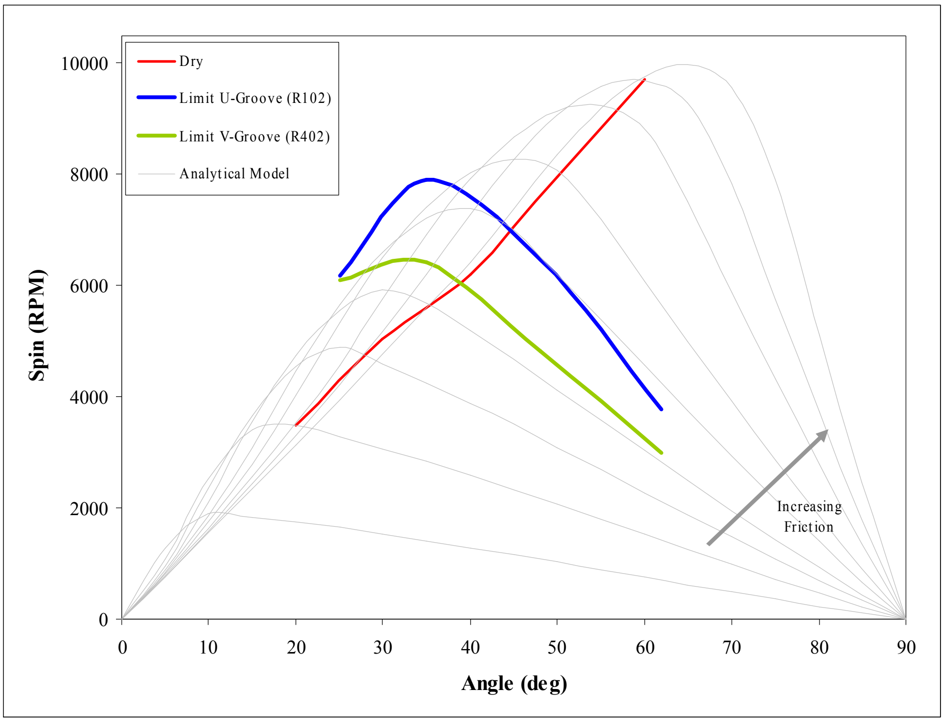


Figure 3.4: Comparison of experimental data and analytical model (Sontara interface, U and V groove plates)

4. Phase I Testing

Plate designs for Phase I isolate individual design variables (shape, width, depth, edge radius and spacing). The results will be presented in a similar fashion. Each section will begin by providing the dimensional specifications of the groove pattern. The spin results over a range of angles will be presented followed by observations on the results.

4.1. Base Plates (B Series)

The base plates are comprised of four different groove profiles where the sidewalls transition from true U to true V grooves. Images of the plate cross sections are provided in Figure 4.1.

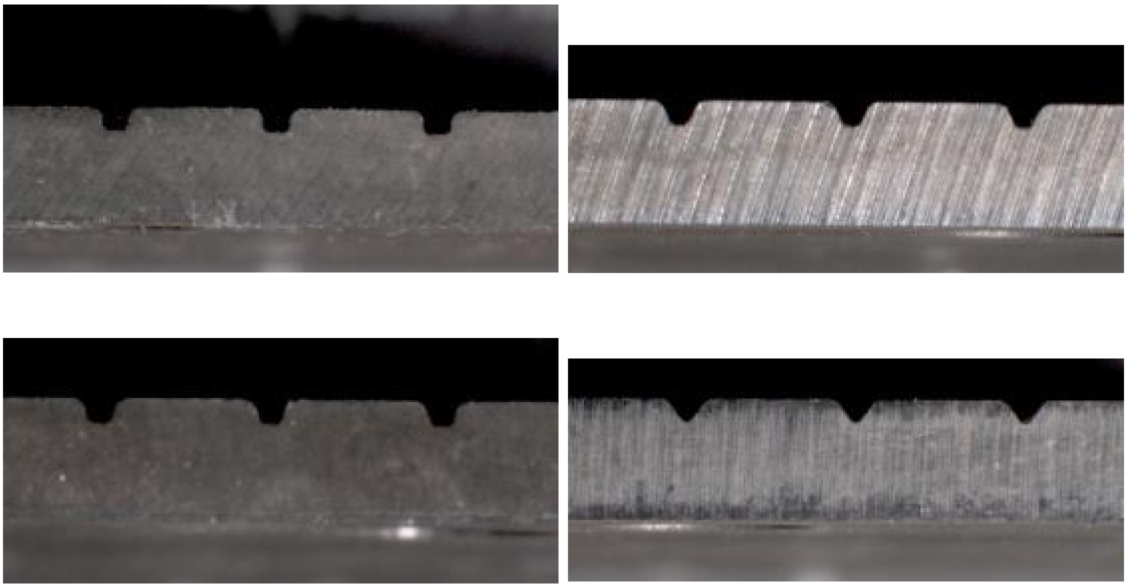


Figure 4.1: Base plate (B-series) groove profiles

Table 4.1: B-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width* (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
B100	90 (U)	0.030	0.020	0.010	0.140
B200	75	0.030	0.020	0.010	0.140
B300	65	0.030	0.020	0.010	0.140
B400	55 (V)	0.030	0.020	0.010	0.140
B000	Grooveless				

* All widths in this study measured using forty five degree tangent lines (see Appendix A.A)

The resulting spin for the two interfacial materials are given in Figures 4.2 and 4.3.

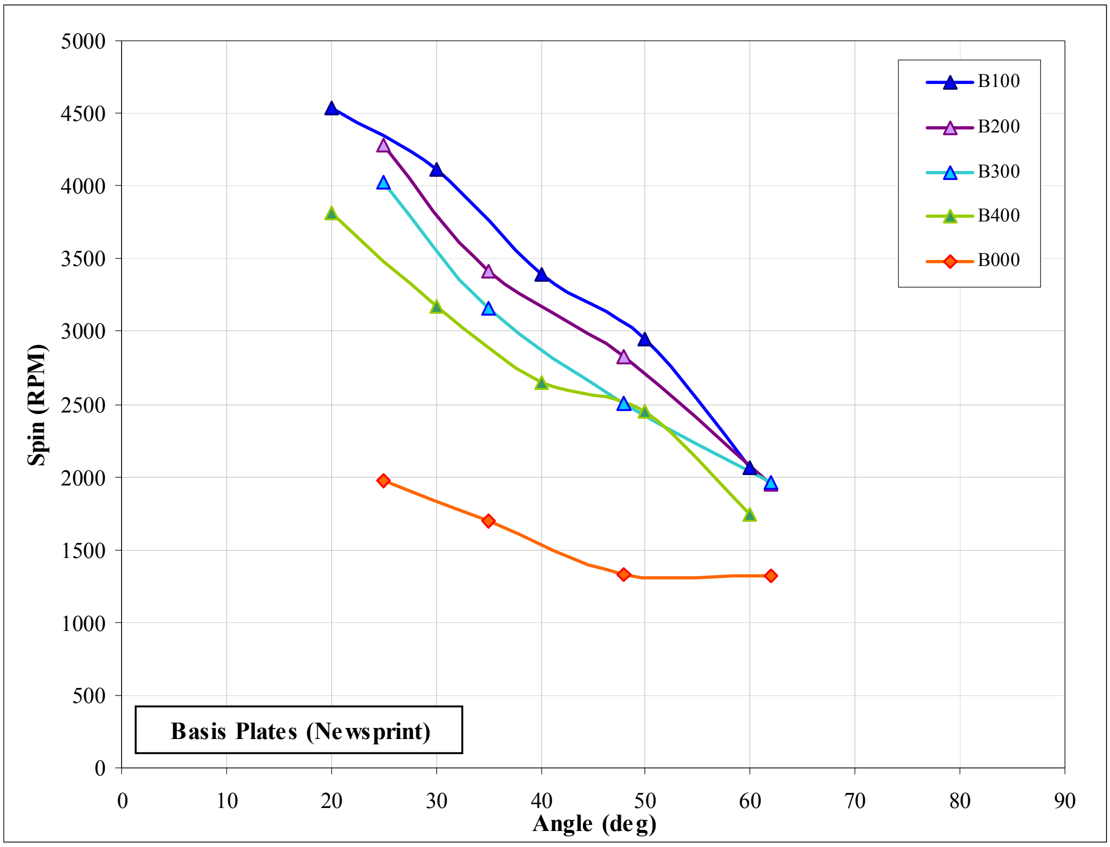


Figure 4.2: Spin results for Base plates (wet newsprint material)

It can be seen in Figure 4.2 that the spin for the U-groove (B100) is superior to that for the V-groove (B400) at all angles. As expected, the semi-U (B200) is close in performance to the U whilst the semi-V (B300) is close in performance to the V. The grooveless plate (B000) performed worse than all of the grooved plates.

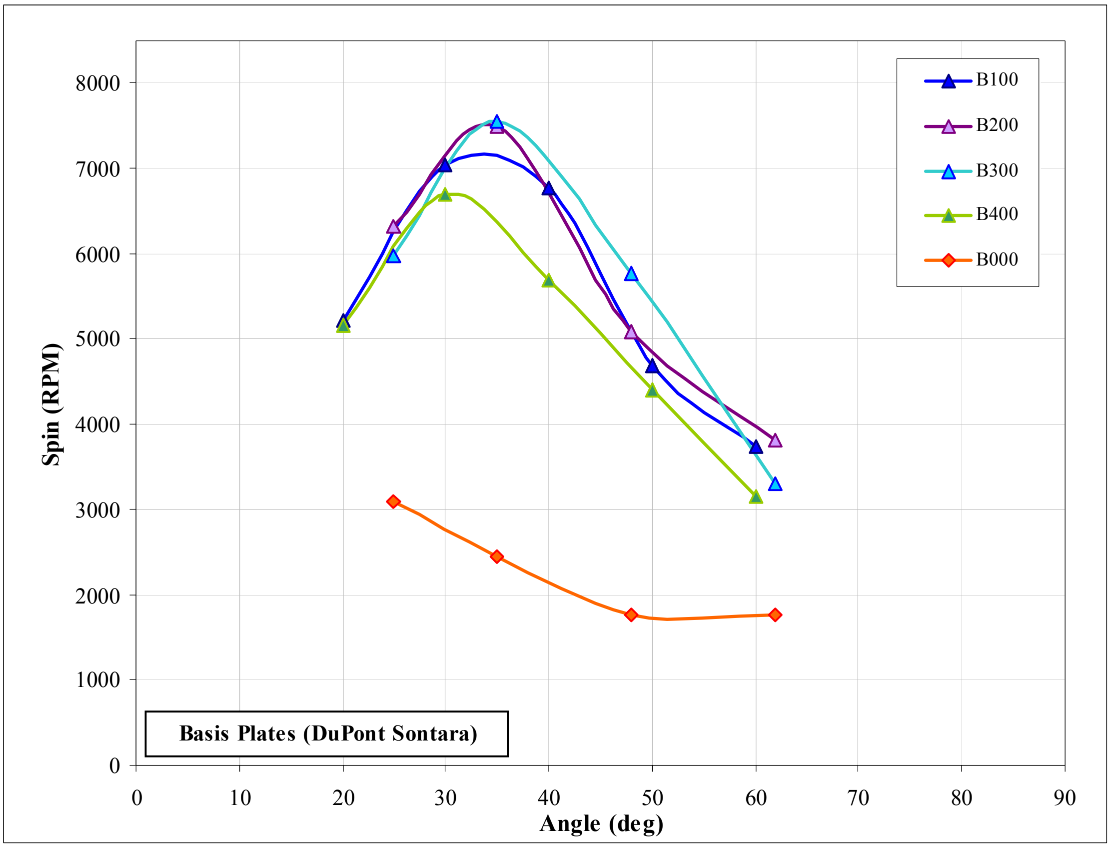


Figure 4.3: Spin results for Base plates (DuPont Sontara material)

The results with the Sontara were not as systematic as the newsprint. The B100, B200 and B300 are indistinguishable from each other. The V-groove (B400) performs worse at most angles than the other shapes. Finally, the grooveless plate performed significantly worse than any of the groove shapes.

4.2. Edge Radius (R Series)

In all of the plates, the edge of the groove meets the land area with a filleted transition. For most plates, the radius of this fillet is 0.010-in. However, this edge radius was varied in the R series plates from 0.0025-in to 0.020-in (note that the B-series complements the R-series by providing the 0.010-in radius plate).

Table 4.2: R-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
R101	90 (U)	0.030	0.020	0.0025	0.140
R102	90 (U)	0.030	0.020	0.005	0.140
R103	90 (U)	0.030	0.020	0.015	0.140
R104	90 (U)	0.030	0.020	0.020	0.140
R201	75	0.030	0.020	0.0025	0.140
R202	75	0.030	0.020	0.005	0.140
R203	75	0.030	0.020	0.015	0.140
R204	75	0.030	0.020	0.020	0.140
R301	65	0.030	0.020	0.0025	0.140
R302	65	0.030	0.020	0.005	0.140
R303	65	0.030	0.020	0.015	0.140
R304	65	0.030	0.020	0.020	0.140
R401	55 (V)	0.030	0.020	0.0025	0.140
R402	55 (V)	0.030	0.020	0.005	0.140
R403	55 (V)	0.030	0.020	0.015	0.140
R404	55 (V)	0.030	0.020	0.020	0.140

The spin results for each base shape are provided in Figures 4.4 through 4.11

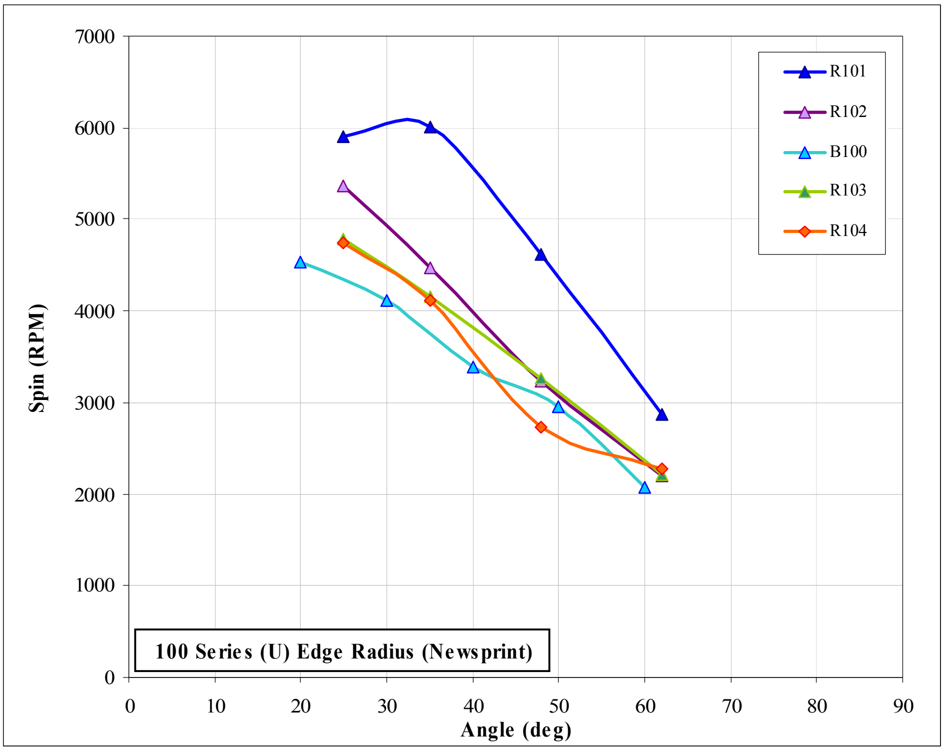


Figure 4.4: Effect of edge radius on spin results for 100 series plates (newsprint)

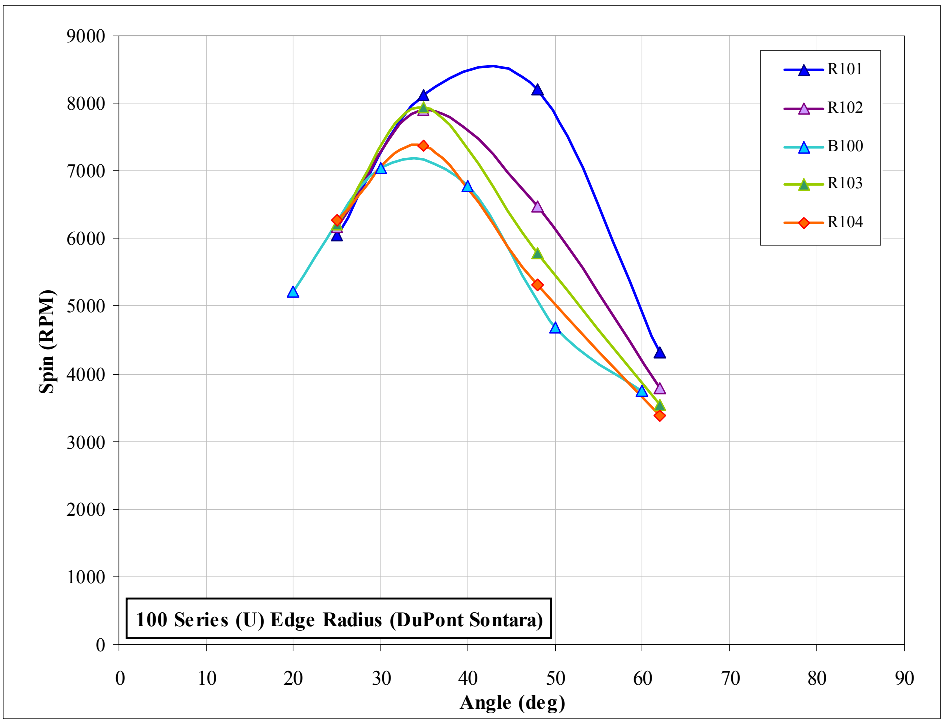


Figure 4.5: Effect of edge radius on spin results for 100 series plates (DuPont Sontara)

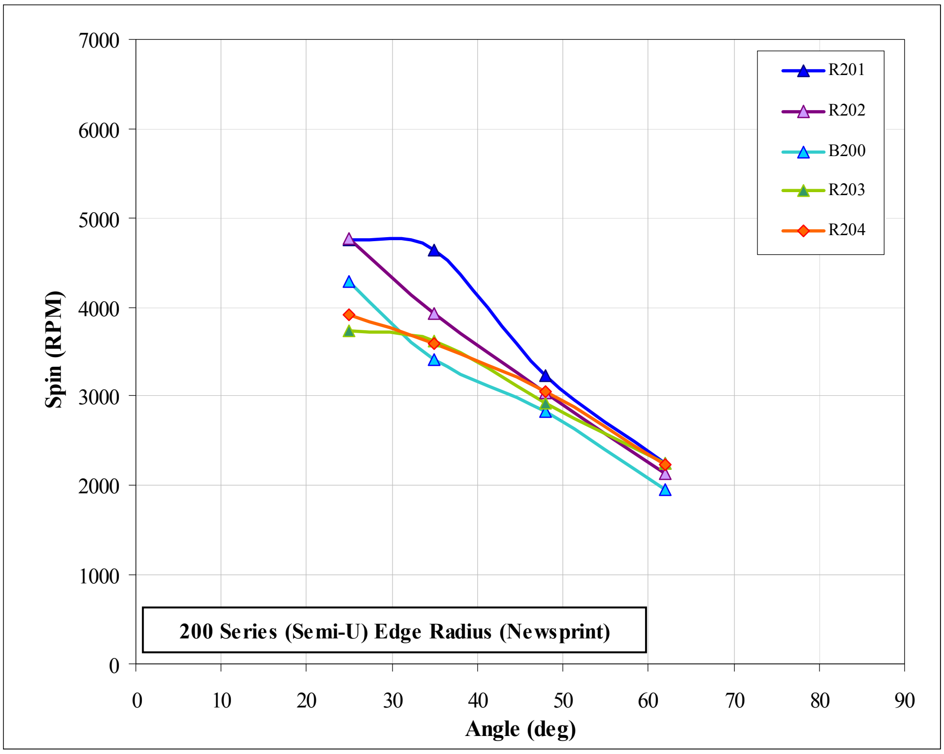


Figure 4.6: Effect of edge radius on spin results for 200 series plates (newsprint)

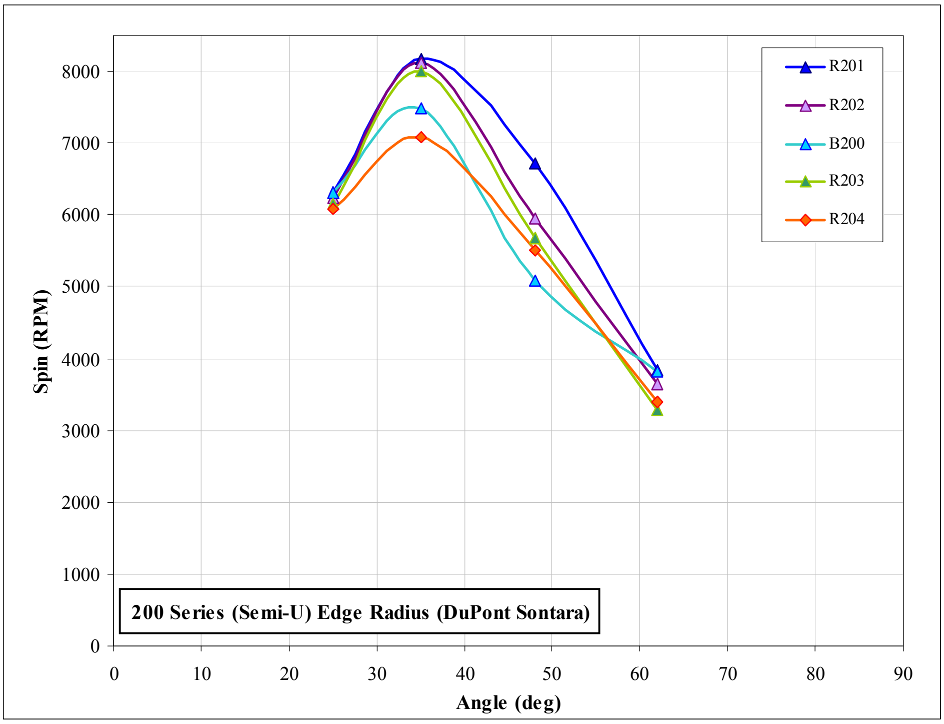


Figure 4.7: Effect of edge radius on spin results for 200 series plates (DuPont Sontara)

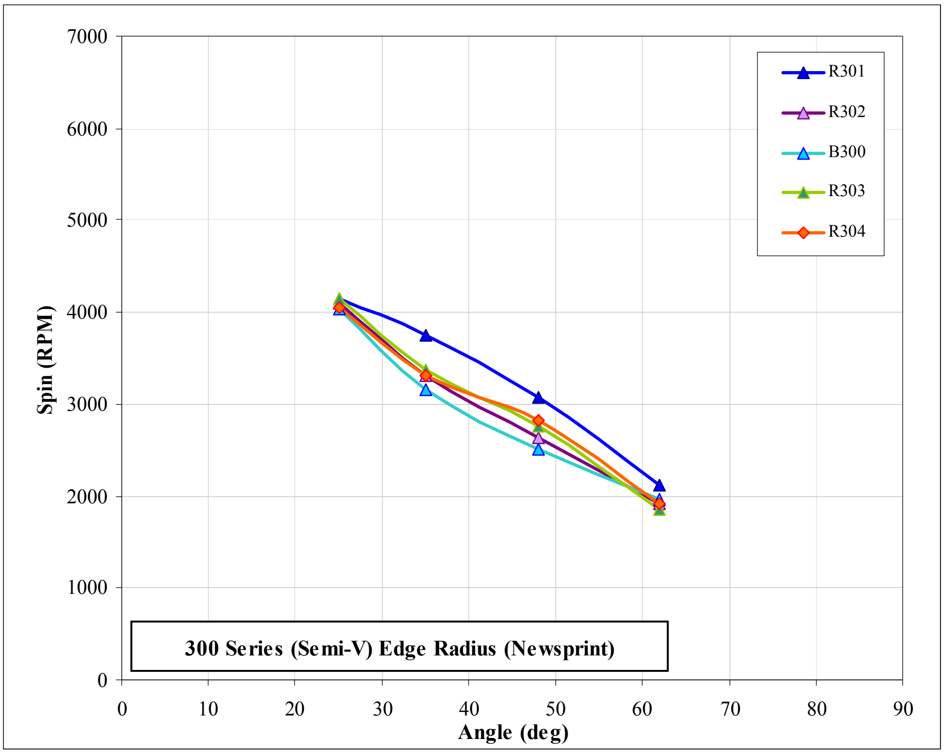


Figure 4.8: Effect of edge radius on spin results for 300 series plates (newsprint)

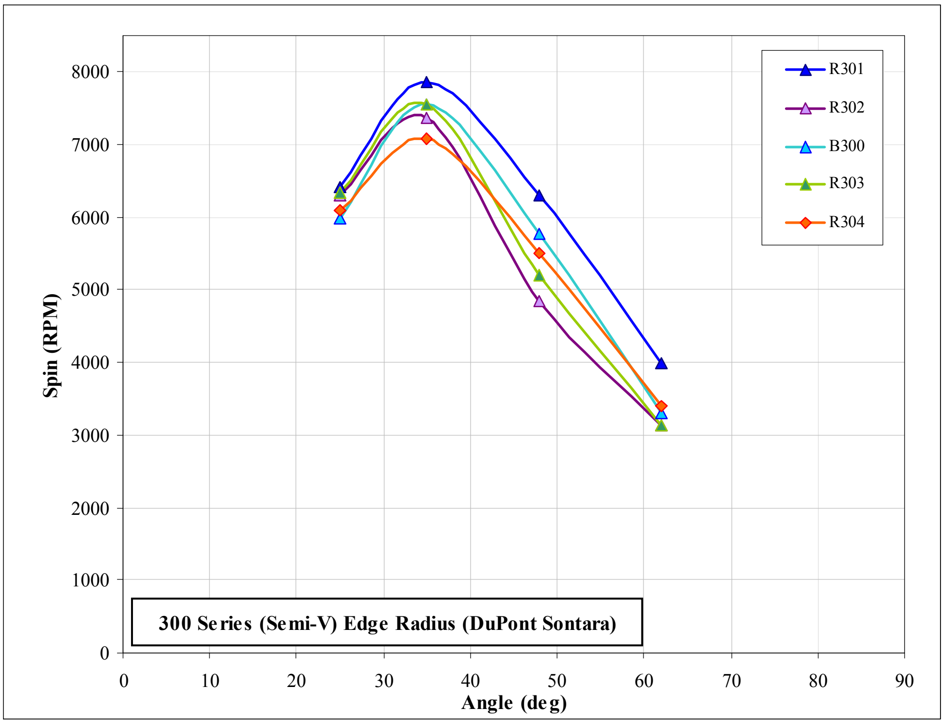


Figure 4.9: Effect of edge radius on spin results for 300 series plates (DuPont Sontara)

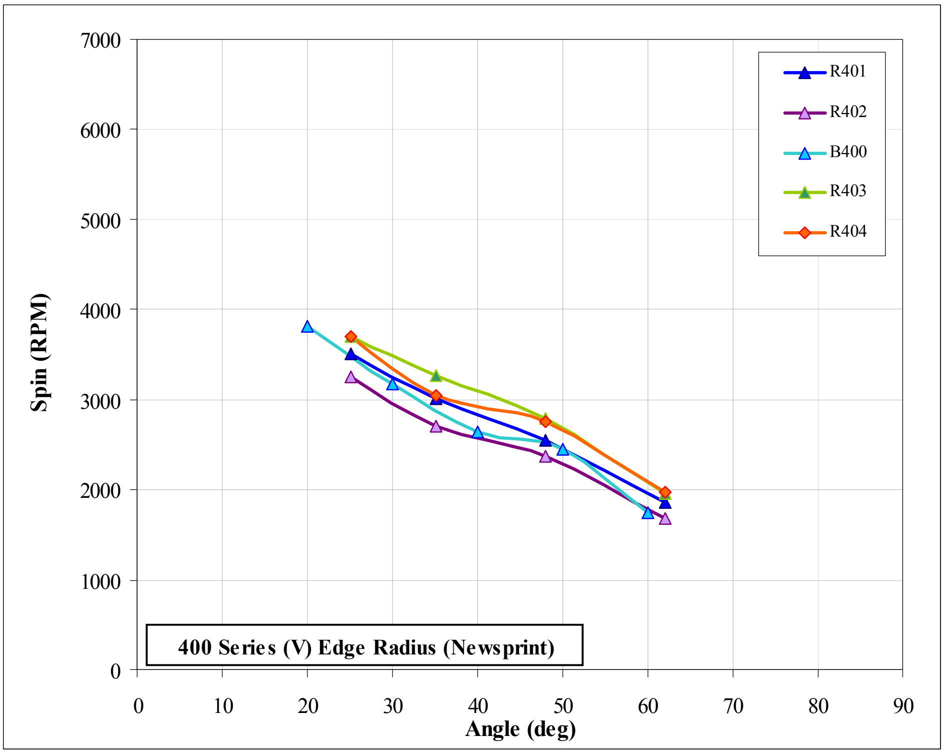


Figure 4.10: Effect of edge radius on spin results for 400 series plates (newsprint)

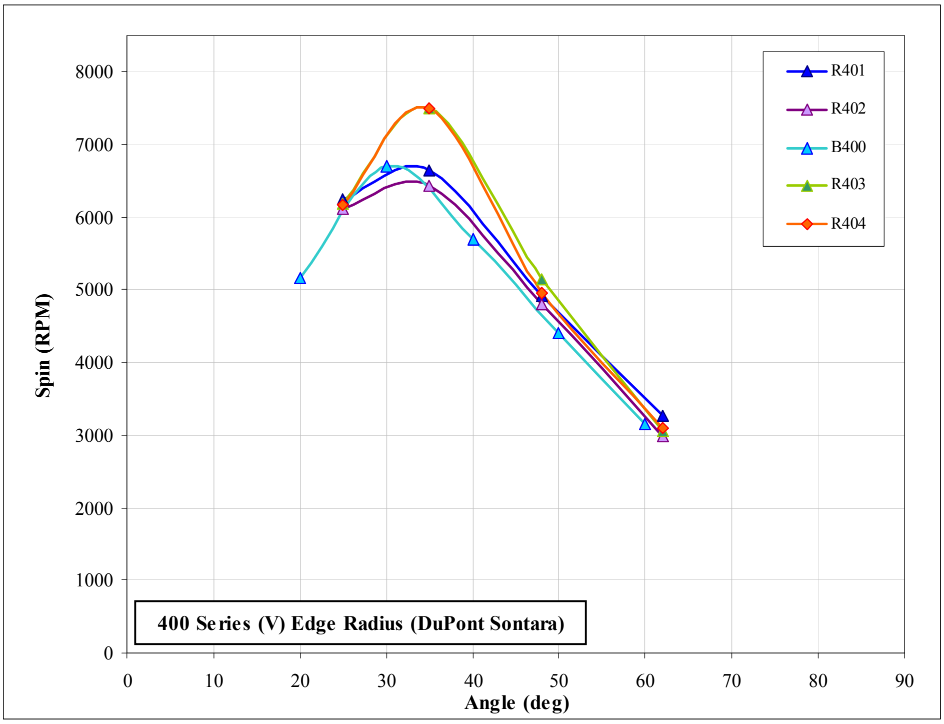


Figure 4.11: Effect of edge radius on spin results for 400 series plates (DuPont Sontara)

The effect of edge radius appears to be dependent on the draught angle of the groove sidewalls. It can be clearly seen in Figures 4.4 and 4.5 that the sharpest edge radius of 0.0025-in (R101) dramatically increases the spin compared with the base radius of 0.010-in (B100). To a lesser degree, the 0.005-in (R102) radius also improves spin. Edge radii larger than 0.010-in however do not appear to have lower performance compared with the base radius.

It can be seen in Figures 4.6 and 4.7 that the 0.0025-in (R201) and 0.005-in (R202) radius also improves spin over the 0.010-in (B200) radius for the semi-U groove (200 series). However, transitioning towards the V-groove (300 and 400 series), it can be seen that the effect of edge radius diminishes. Only the sharpest edge radius for the semi-V profile (R301) improves spin compared to the duller edges. For the true V-groove (400 series), edge radius does not consistently affect the resulting spin rate

The thirty five degree impact with newsprint interfacial material demonstrates the effect of edge radii on the various groove shapes. These results are plotted in Figure 4.12.

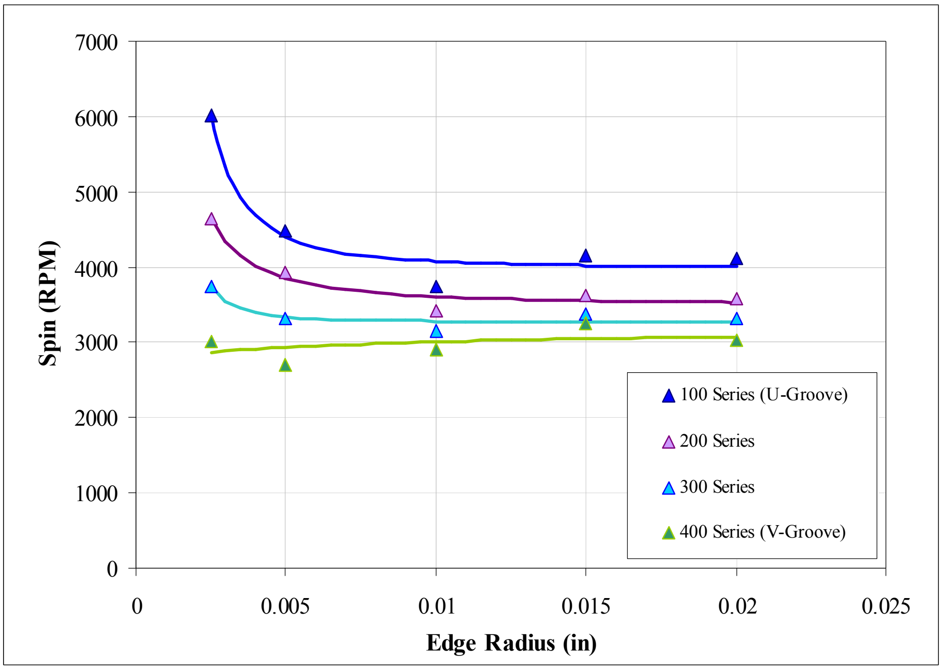


Figure 4.12: Effect of edge radius on 35 degree spin results (newsprint)

A function of the form:

$$\omega = \frac{A}{R_{edge}^{k}} + B \qquad (4.1)$$

has been fit in a least squares sense to the data of Figure 4.12 (where ω is the spin, R_{edge} is the edge radius and A, B and k are fitted parameters). It is clear in Figure 4.12 that the edge radius has the greatest effect on the U shaped groove with diminishing effect as the groove shape transitions towards a V groove.

4.3. Spacing (S Series)

For purposes of this project, spacing is the centre to centre distance, or more appropriately, the pitch. The current groove specification permits the edge to edge distance to be no closer than three times the width of the groove (as measured from 30 degree tangency points), which itself is limited to 0.035-in. Therefore, for maximum width grooves, the minimum allowable edge to edge distance would be 0.105-in. Equivalently, the minimum allowable pitch of such a configuration would be 0.140-in, which is 0.105-in plus the width of the groove of 0.035-in. The spacing of the S series test plates was varied by ±0.035-in for all four groove shapes. The U and semi-U profiles plates additionally had a spacing of 0.210-in. It should be noted that these last two plates (S103 and S203) were formally part of Phase II designs but have been included here for comparison purposes.

Table 4.3: S-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
S101	90 (U)	0.030	0.020	0.010	0.105
S102	90 (U)	0.030	0.020	0.010	0.175
S103	90 (U)	0.030	0.020	0.010	0.210
S201	75	0.030	0.020	0.010	0.105
S202	75	0.030	0.020	0.010	0.175
S203	75	0.030	0.020	0.010	0.210
S301	65	0.030	0.020	0.010	0.105
S302	65	0.030	0.020	0.010	0.175
S401	55 (V)	0.030	0.020	0.010	0.105
S402	55 (V)	0.030	0.020	0.010	0.175

The effect of spacing on the four groove shapes are plotted in Figures 4.13 through 4.20.

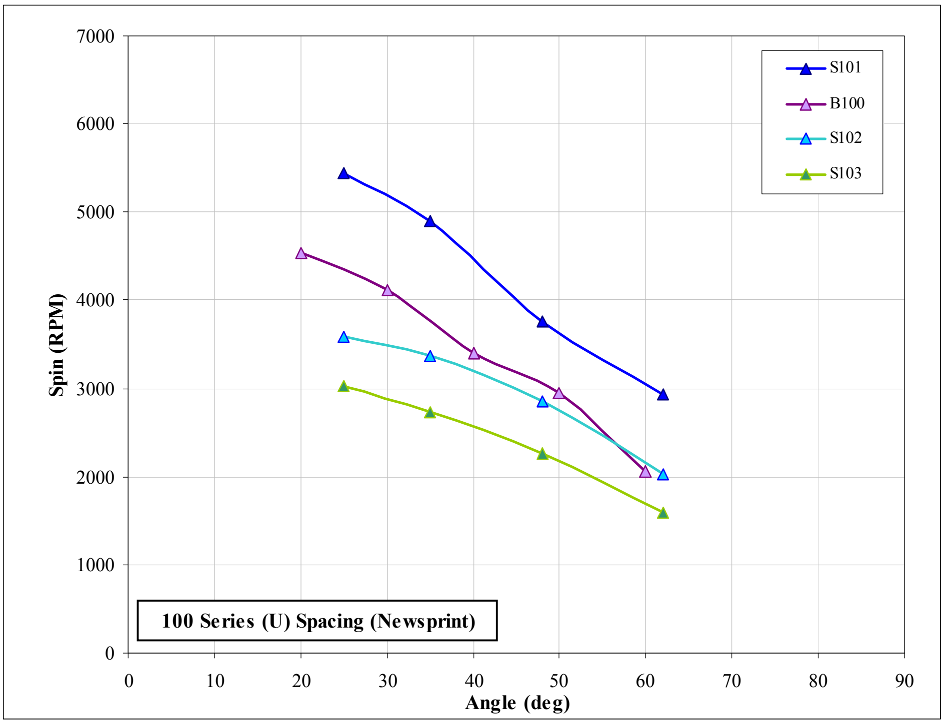


Figure 4.13: Effect of spacing on spin results for 100 series plates (newsprint)

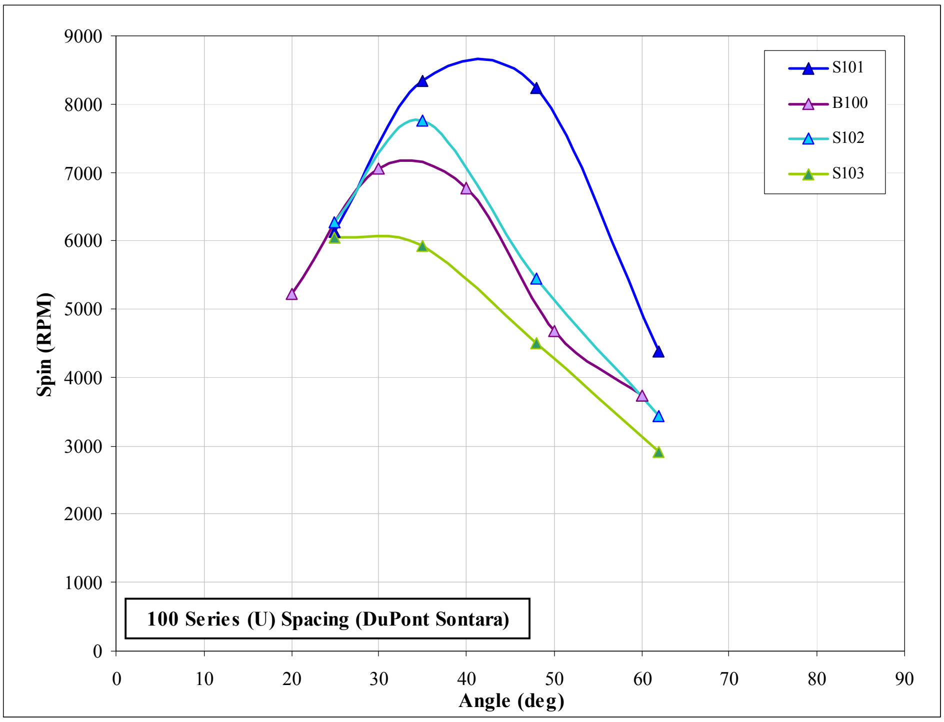


Figure 4.14: Effect of spacing on spin results for 100 series plates (DuPont Sontara)

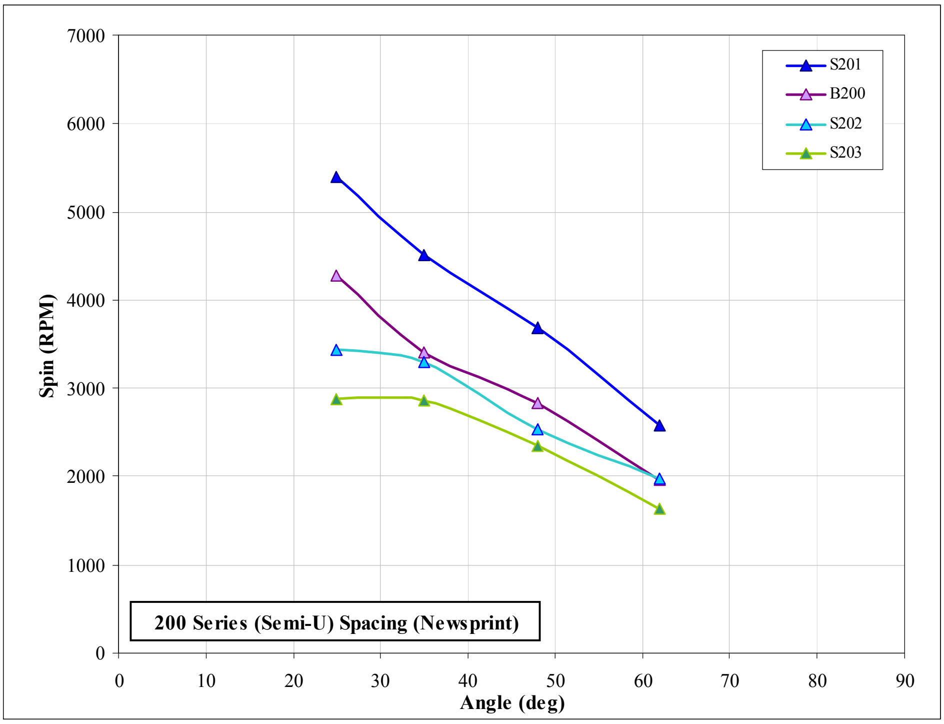


Figure 4.15: Effect of spacing on spin results for 200 series plates (newsprint)

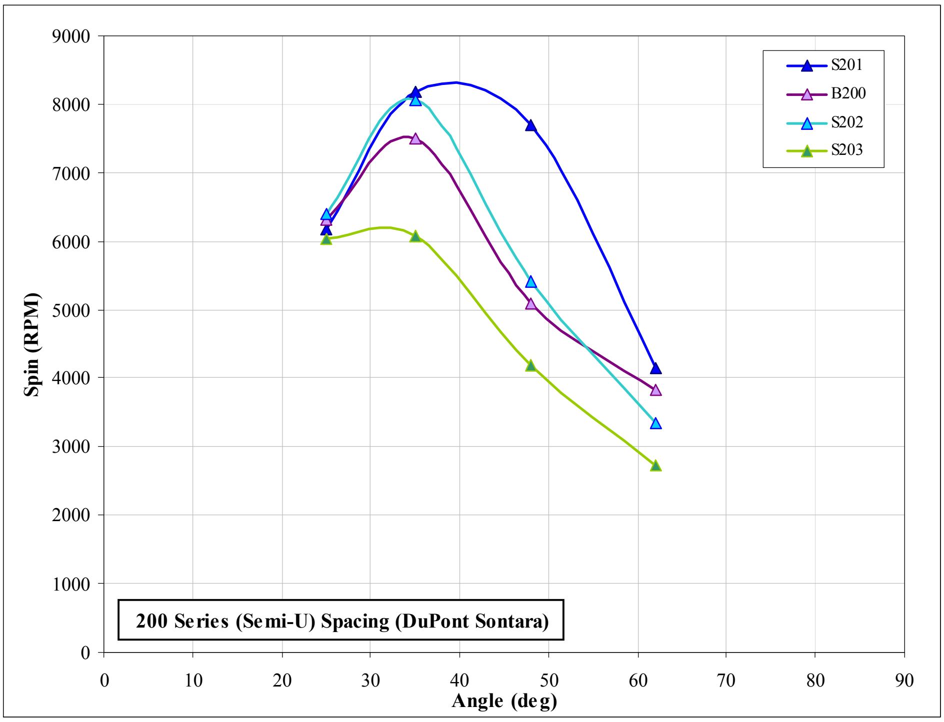


Figure 4.16: Effect of spacing on spin results for 200 series plates (DuPont Sontara)

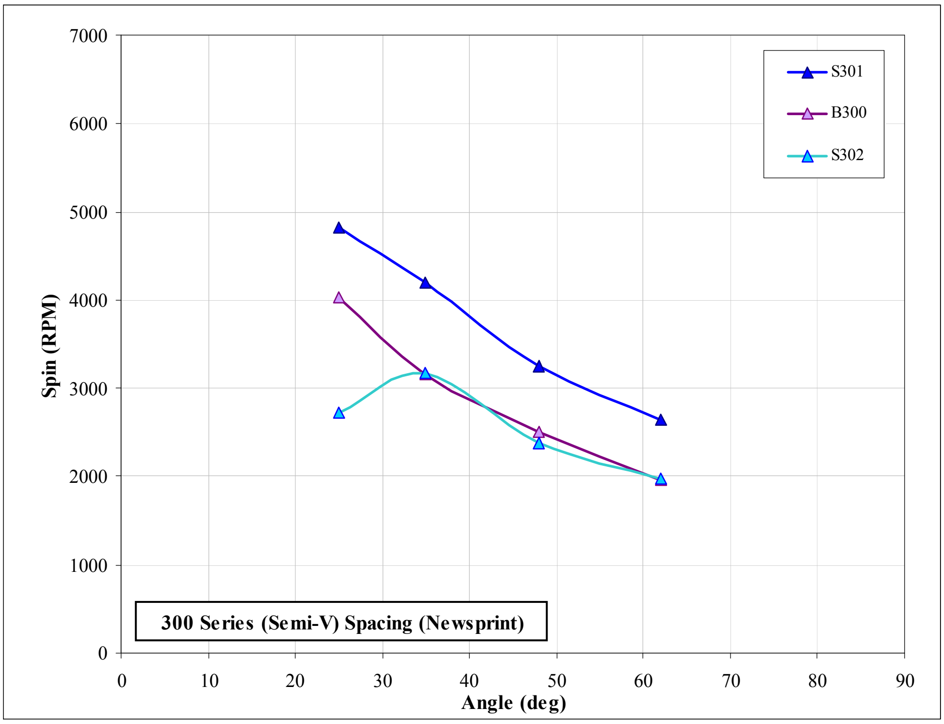


Figure 4.17: Effect of spacing on spin results for 300 series plates (newsprint)

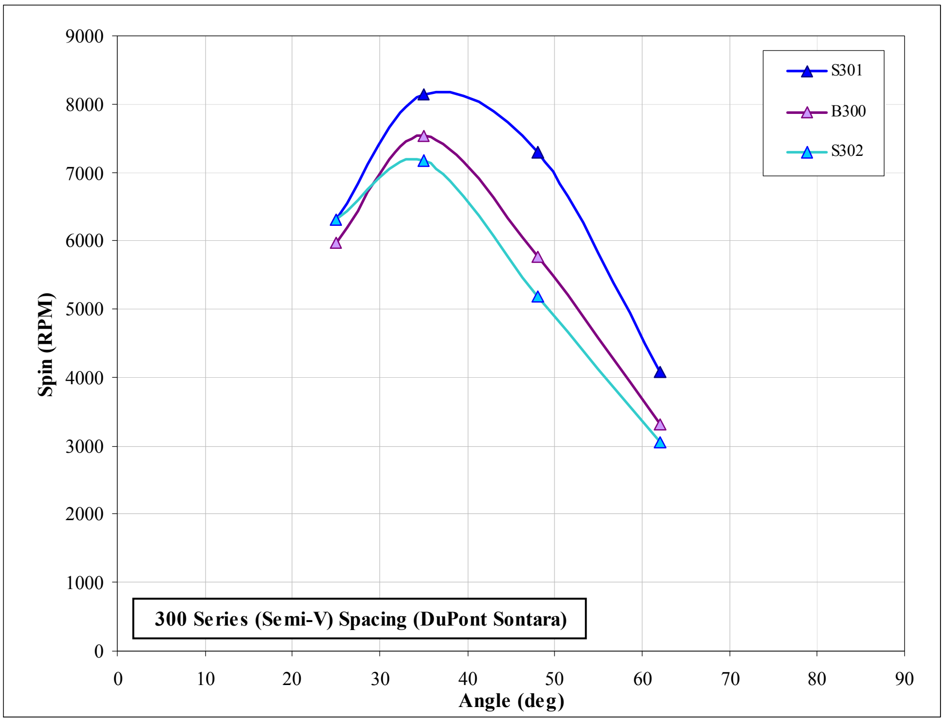


Figure 4.18: Effect of spacing on spin results for 300 series plates (DuPont Sontara)

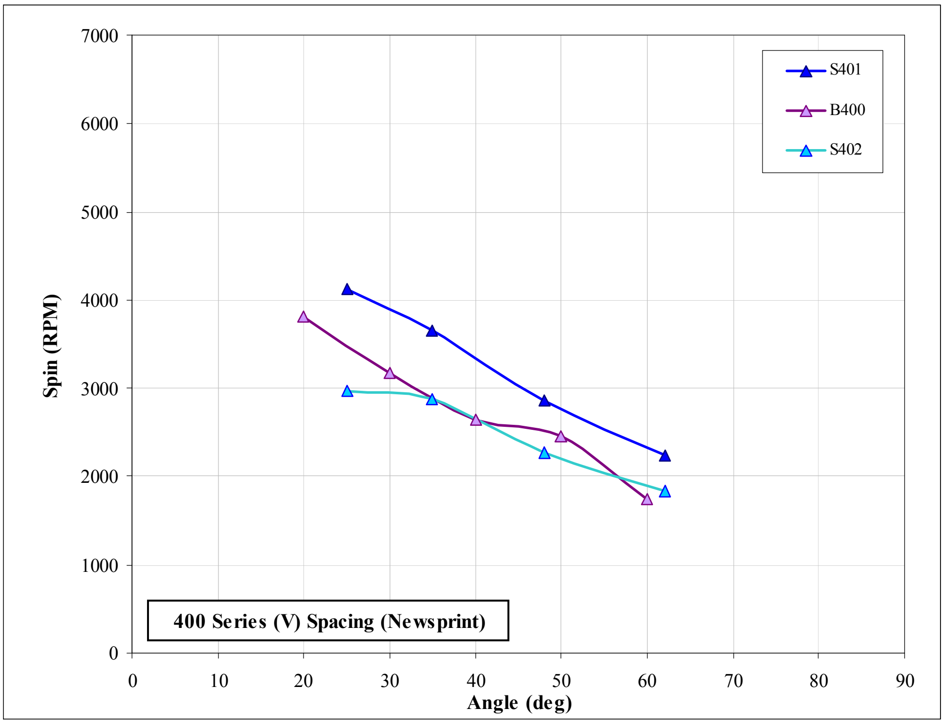


Figure 4.19: Effect of spacing on spin results for 400 series plates (newsprint)

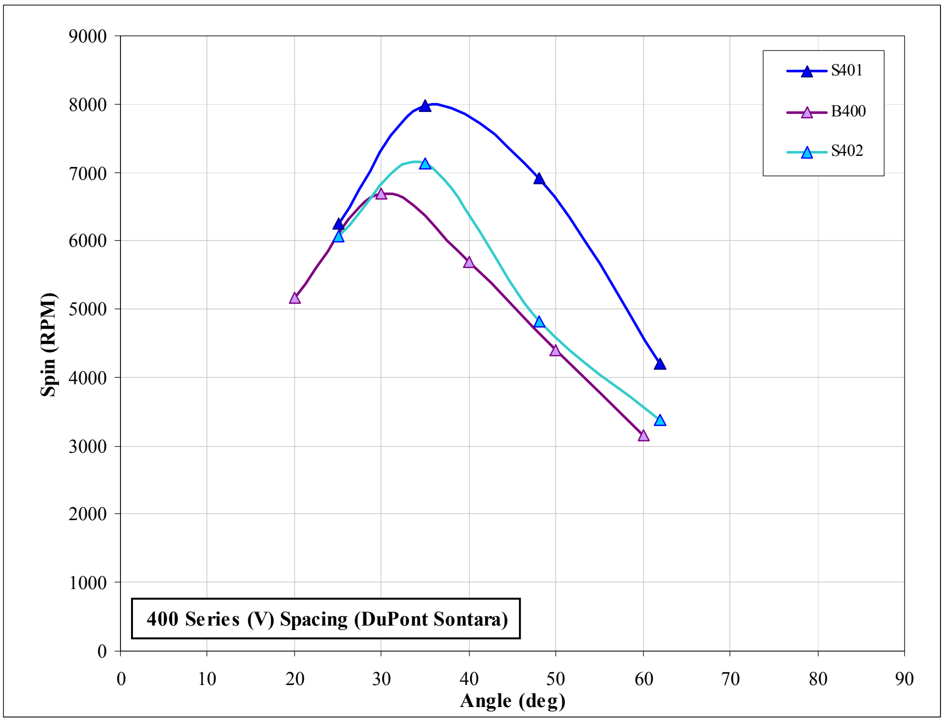


Figure 4.20: Effect of spacing on spin results for 400 series plates (DuPont Sontara)

It may be seen in Figures 4.13 through 4.20, that decreasing the spacing of the grooves clearly increases the spin performance of all groove shapes. The effect of increasing spacing is less certain. At low angles with newsprint, the spin performance of all the groove shapes was reduced with increasing spacing. However, at other angles and with the Sontara material, increasing the pitch distance from 0.140-in to 0.175-in did not significantly reduce spin. This may be a result of the finite nature of the contact patch. That is, changing the spacing from 0.140-in to 0.175-in may not have consistently increased the number of grooves in contact with the ball.

Further increasing the pitch distance on the U and semi-U groove profiles to 0.210-in however did have the expected result of lowering spin performance as may be seen in Figures 4.13 through 4.16.

4.4. Depth (D Series)

The limit of groove depth is currently 0.020-in. Test plates were generated with depths reduced to 0.010-in and 0.015-in for all groove shapes. In addition, where possible, groove depths were increased to 0.025-in and 0.0394-in (V-groove depth cannot be increased whilst maintaining a sidewall draught angle of 55 degrees for example).

Table 4.3: D-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
D101	90 (U)	0.030	0.010	0.010	0.140
D102	90 (U)	0.030	0.015	0.010	0.140
D103	90 (U)	0.030	0.025	0.010	0.140
D104	90 (U)	0.030	0.0394	0.010	0.140
D201	75	0.030	0.010	0.010	0.140
D202	75	0.030	0.015	0.010	0.140
D203	75	0.030	0.025	0.010	0.140
D204	75	0.030	0.0394	0.010	0.140
D301	65	0.030	0.010	0.010	0.140
D302	65	0.030	0.015	0.010	0.140
D303	65	0.030	0.025	0.010	0.140
D401	55 (V)	0.030	0.010	0.010	0.140
D402	55 (V)	0.030	0.015	0.010	0.140

The effect of varying groove depth on spin for the four groove shapes are plotted in Figures 4.21 through 4.28.

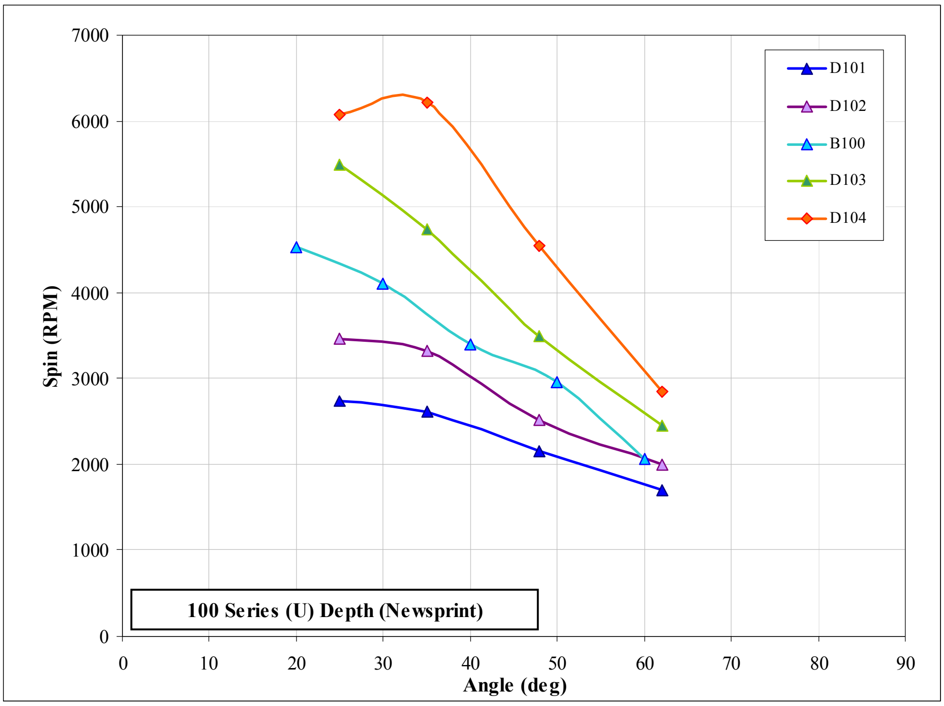


Figure 4.21: Effect of depth on spin results for 100 series plates (newsprint)

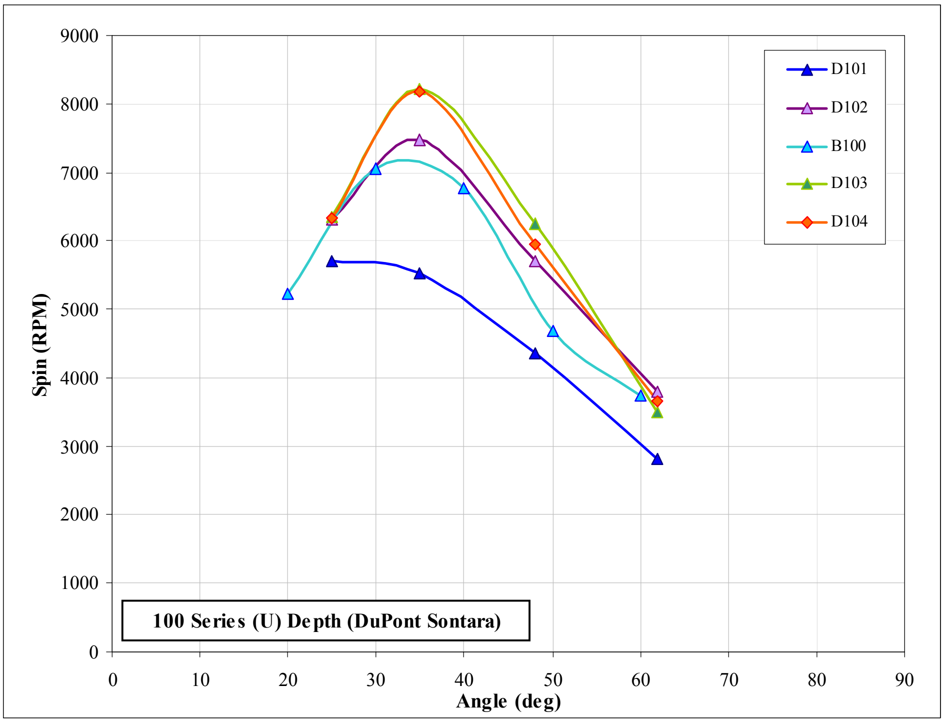


Figure 4.22: Effect of depth on spin results for 100 series plates (DuPont Sontara)

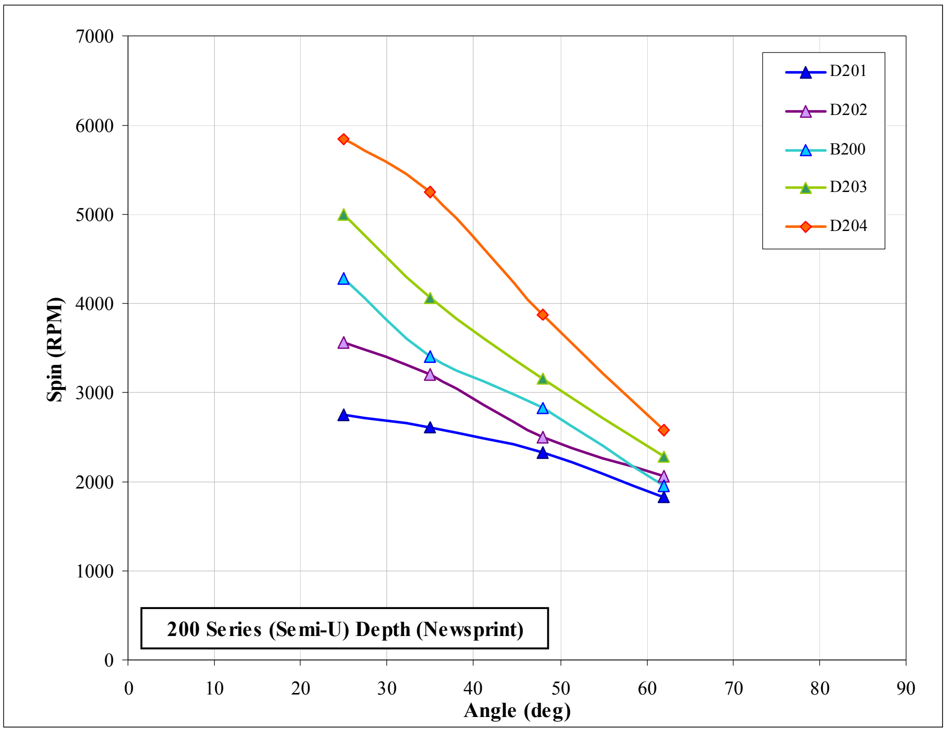


Figure 4.23: Effect of depth on spin results for 200 series plates (newsprint)

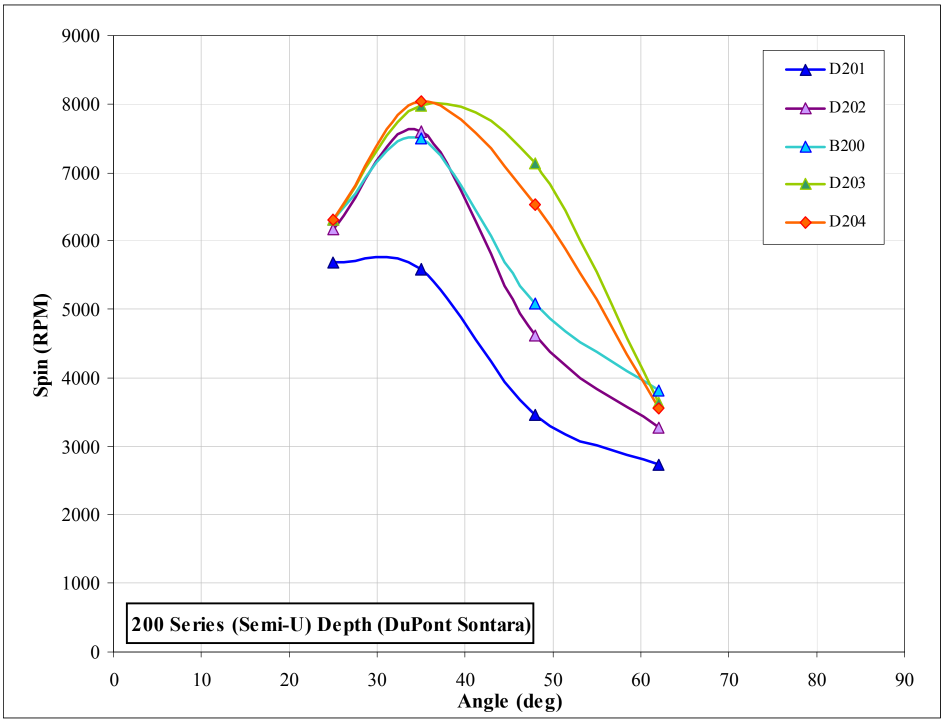


Figure 4.24: Effect of depth on spin results for 200 series plates (DuPont Sontara)

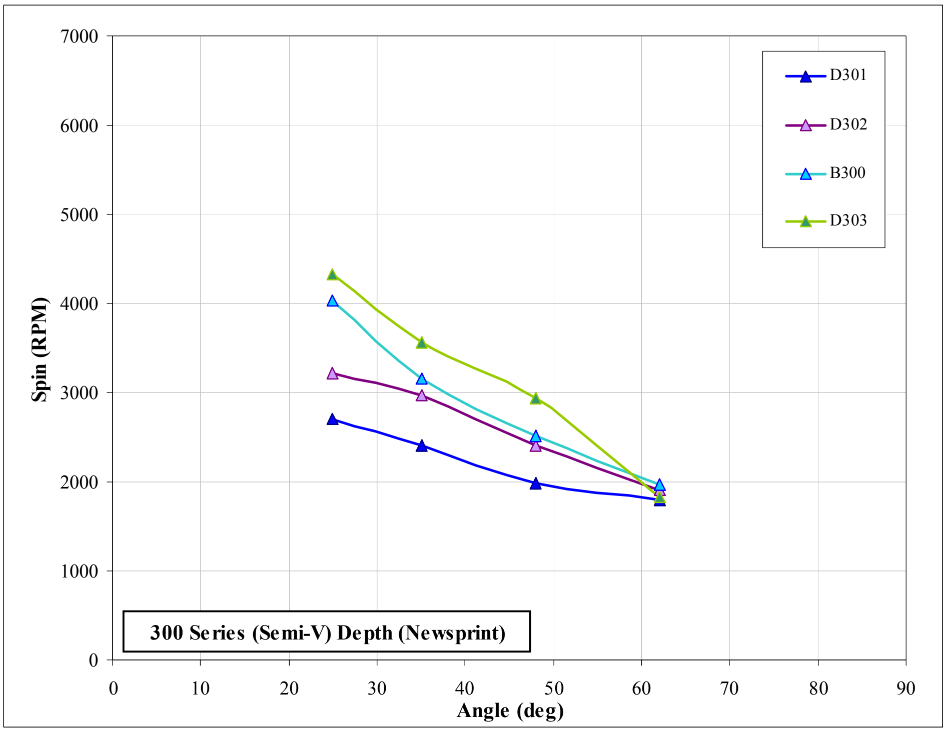


Figure 4.25: Effect of depth on spin results for 300 series plates (newsprint)

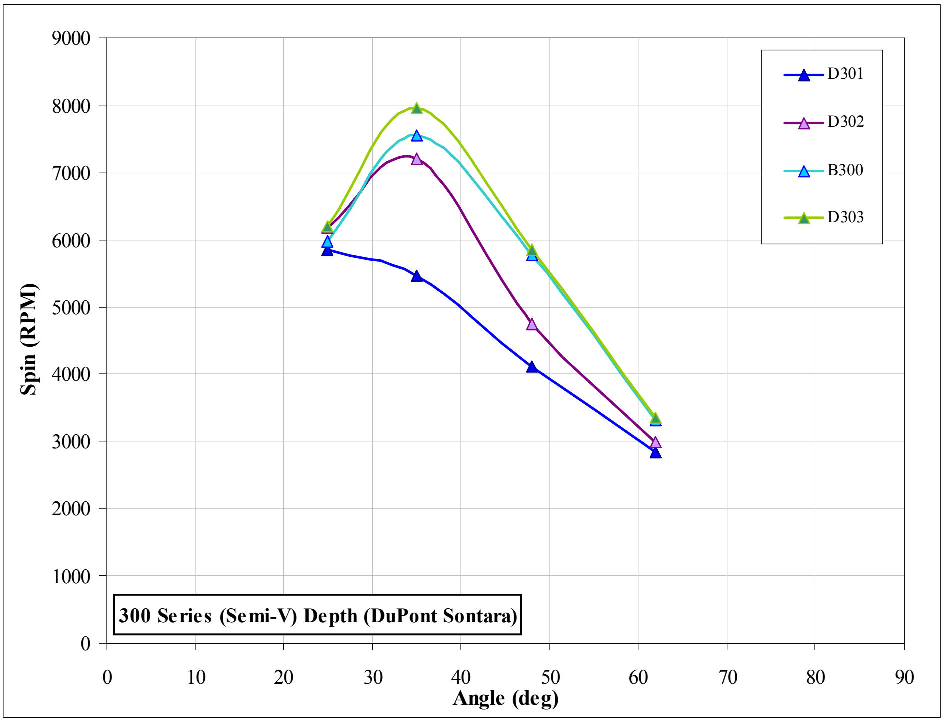


Figure 4.26: Effect of depth on spin results for 300 series plates (DuPont Sontara)

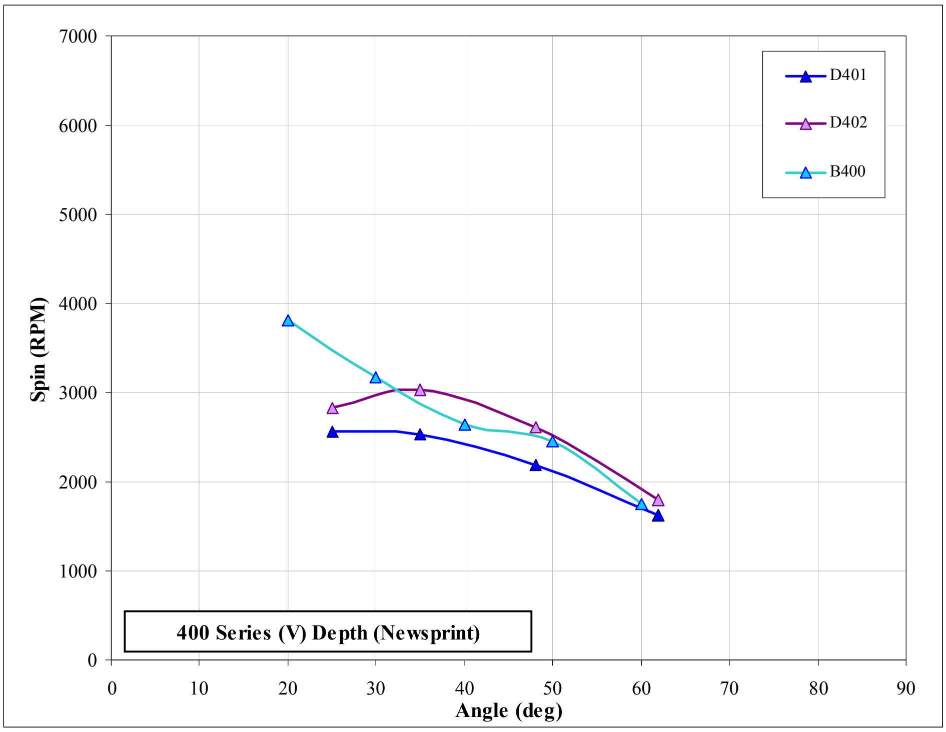


Figure 4.27: Effect of depth on spin results for 400 series plates (newsprint)

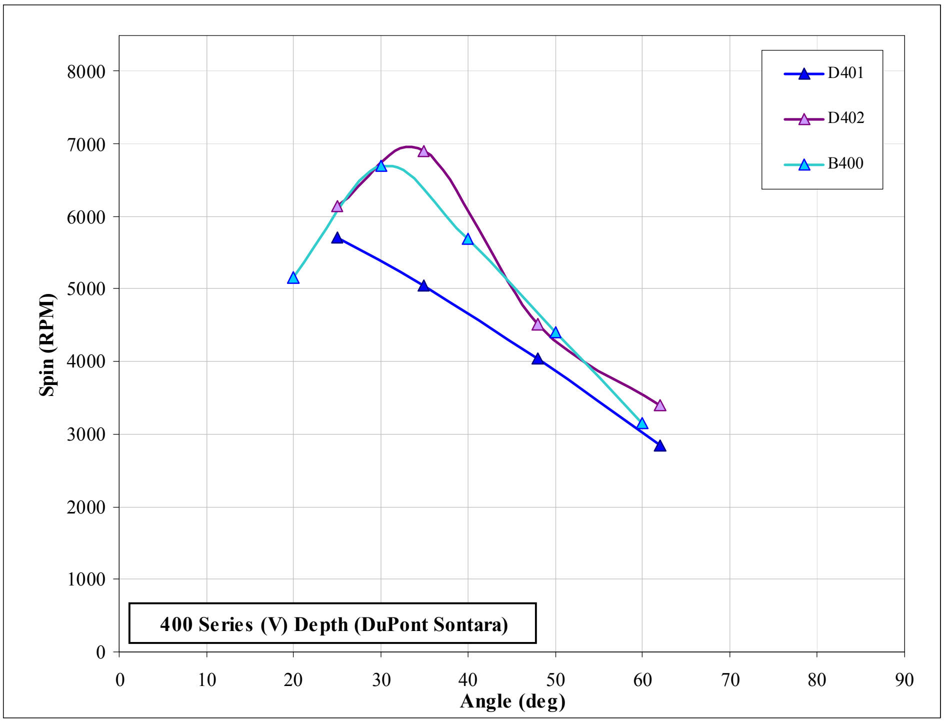


Figure 4.28: Effect of depth on spin results for 400 series plates (DuPont Sontara)

For the newspaper interface (Figures 4.21, 4.23, 4.25 and 4.27), it may be seen that, in almost all cases, spin is directly controlled by groove depth. Again, the thirty five degree impact most clearly demonstrates this as plotted Figure 4.29. It can be seen in this figure that, except for the V-groove, the spin increases with depth. Generally, similar behaviour is exhibited with the Sontara. However, it appears that beyond a depth of 0.025-in, no additional benefit is realised (see Figures 4.22 and 4.24).

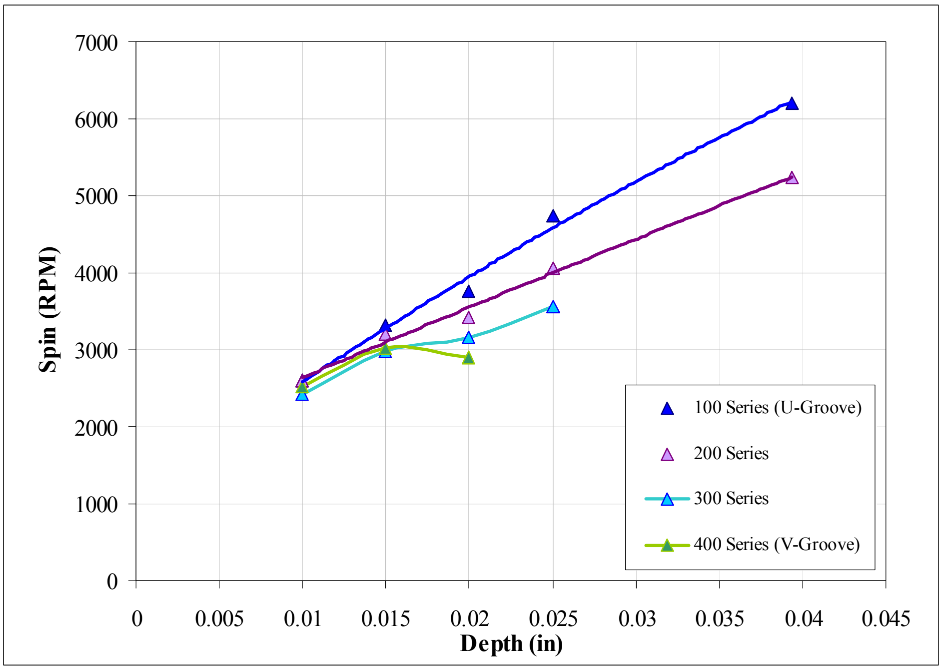


Figure 4.29: Effect of depth on 35 degree spin results (newsprint)

4.5. Width (W-Series)

Groove width is currently limited to 0.035-in measured from the thirty degree tangency points on the edges of the groove. In order to minimise changes in groove cross-sectional area as a function of edge radius, groove widths in this study were measured at the forty five degree tangency points (see Appendix A.A). A groove with a 0.010-in edge radius and a width of 0.035-in measured via thirty degree tangency points would measure approximately 0.030-in wide at the forty five degree tangency points. Groove widths were varied from 0.020-in to 0.035-in (approximately equivalent to 0.025-in to 0.040-in using thirty degree tangency points) where possible. For example, the V-groove could only be widened whilst maintaining a fifty five degree draught angle.

Table 4.4: W-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
W101	90 (U)	0.020	0.020	0.010	0.140
W102	90 (U)	0.025	0.020	0.010	0.140
W103	90 (U)	0.035	0.020	0.010	0.140
W201	75	0.020	0.020	0.010	0.140
W202	75	0.025	0.020	0.010	0.140
W203	75	0.035	0.020	0.010	0.140
W302	65	0.025	0.020	0.010	0.140
W303	65	0.035	0.020	0.010	0.140
W403	55 (V)	0.035	0.020	0.010	0.140

The effect of width on spin is plotted in Figures 4.30 through 4.37.

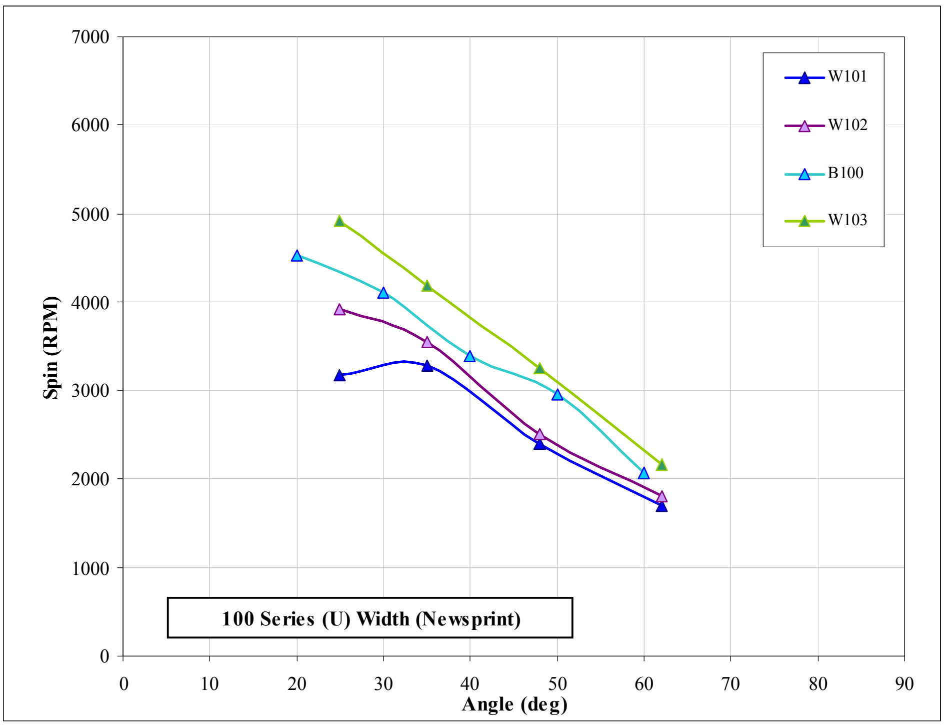


Figure 4.30: Effect of groove width on spin results for 100 series plates (newsprint)

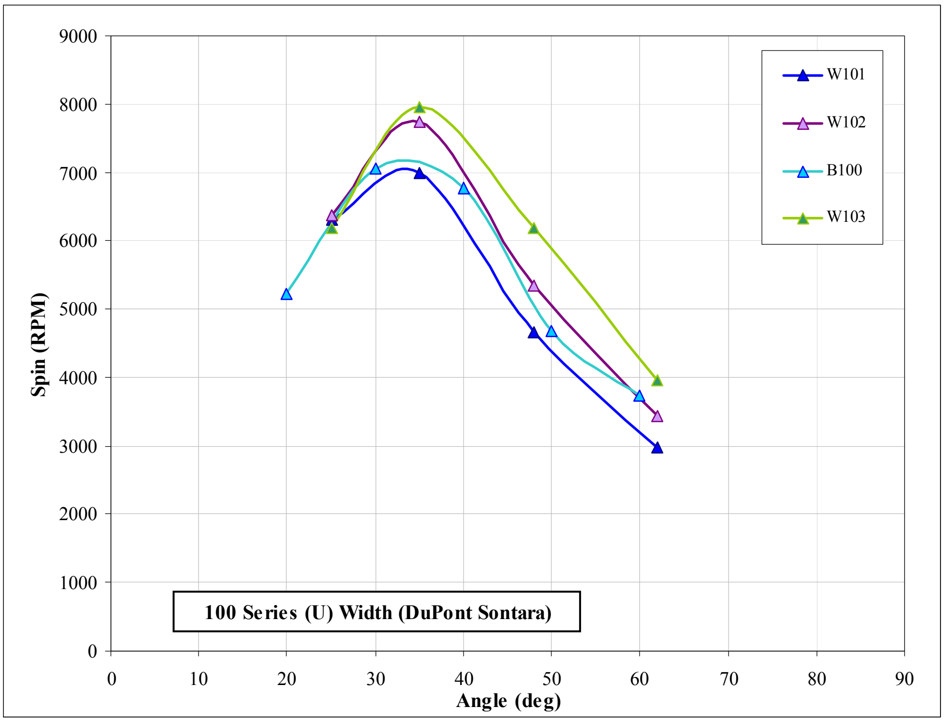


Figure 4.31: Effect of width on spin results for 100 series plates (DuPont Sontara)

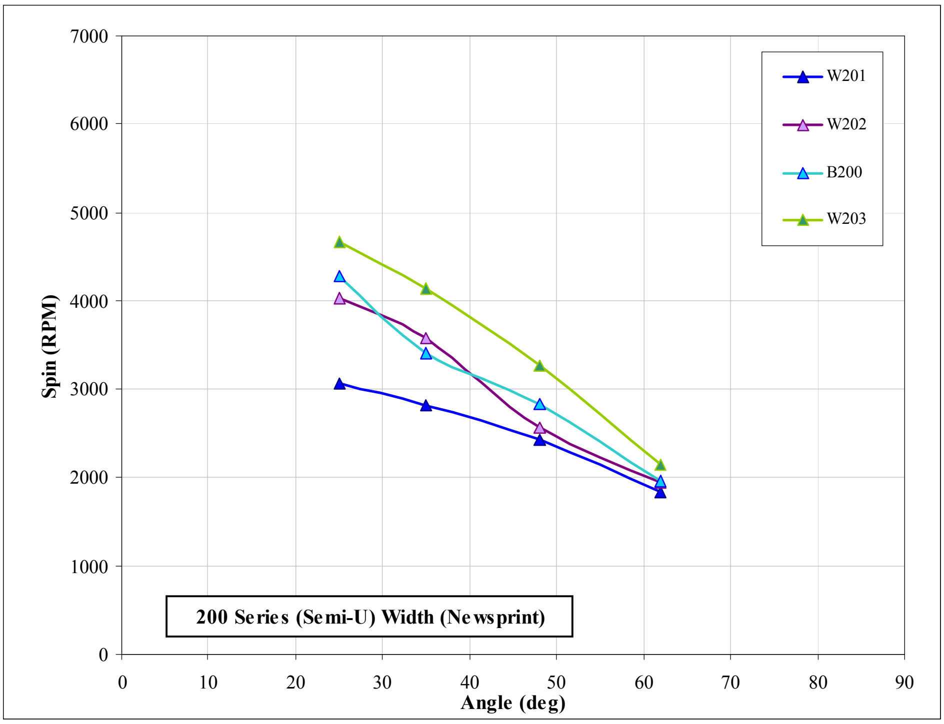


Figure 4.32: Effect of width on spin results for 200 series plates (newsprint)

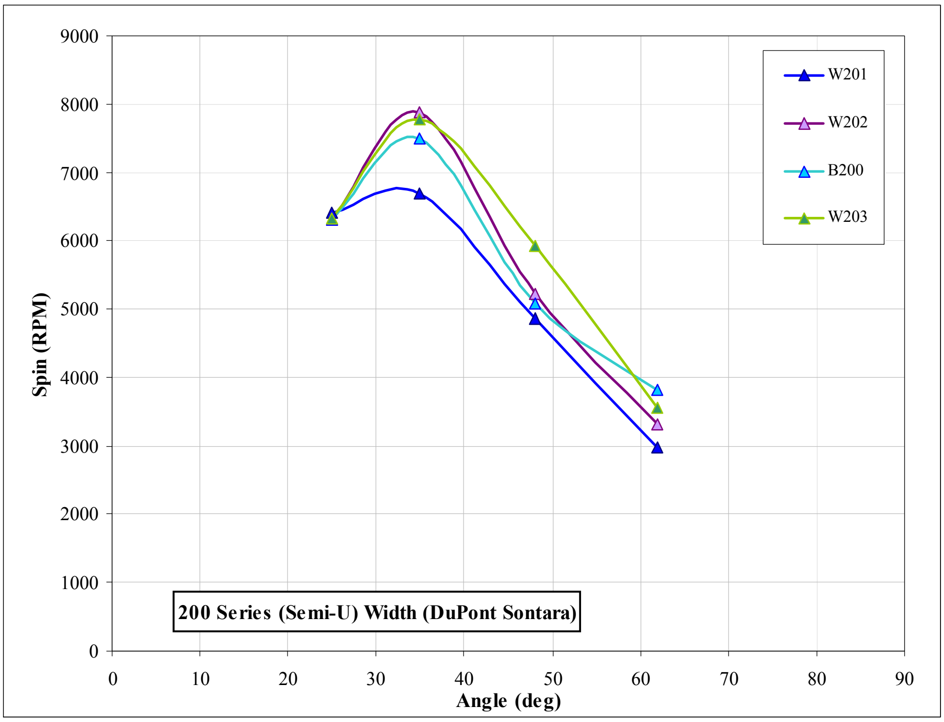


Figure 4.33: Effect of width on spin results for 200 series plates (DuPont Sontara)

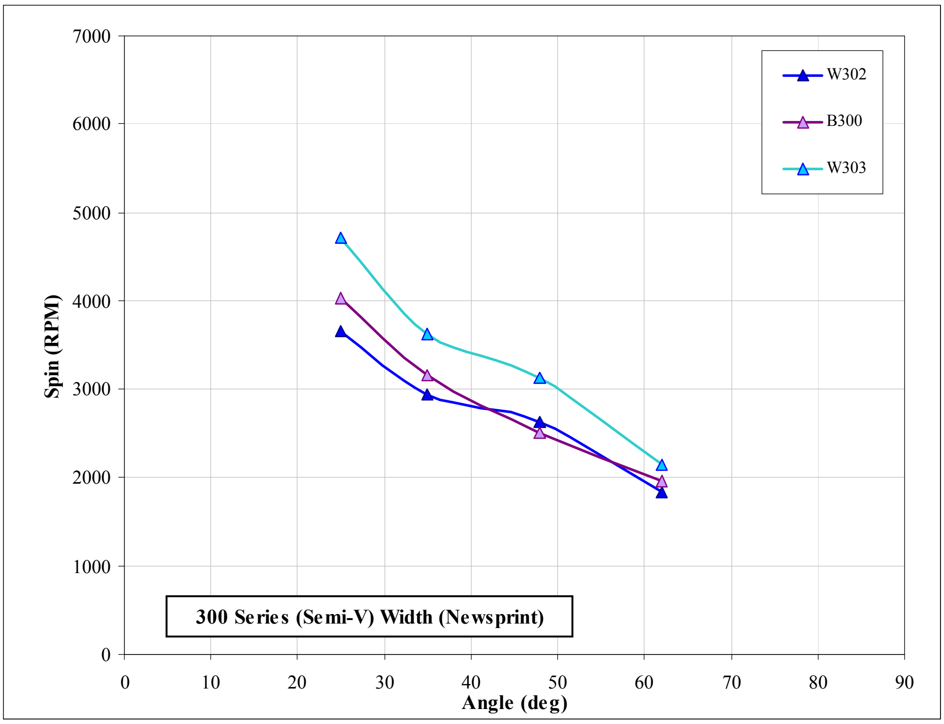


Figure 4.34: Effect of width on spin results for 300 series plates (newsprint)

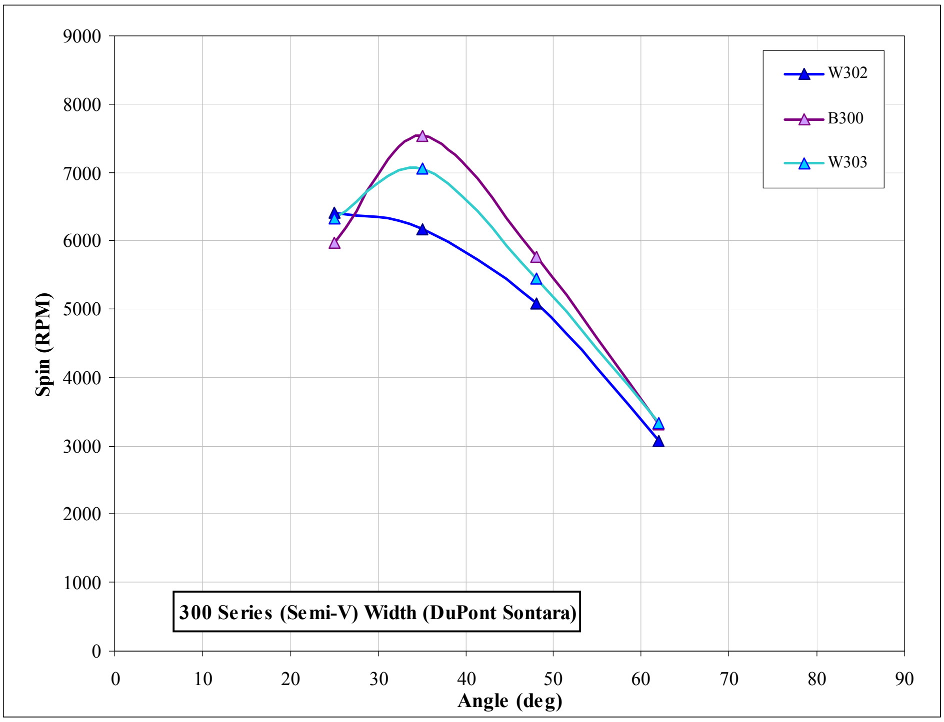


Figure 4.35: Effect of width on spin results for 300 series plates (DuPont Sontara)

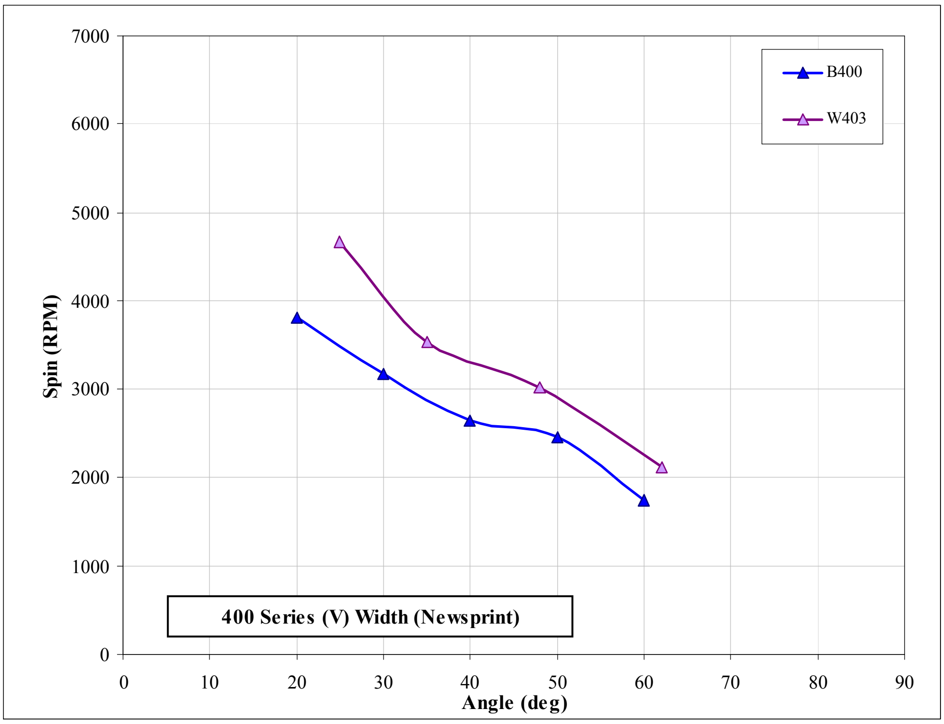


Figure 4.36: Effect of width on spin results for 400 series plates (newsprint)

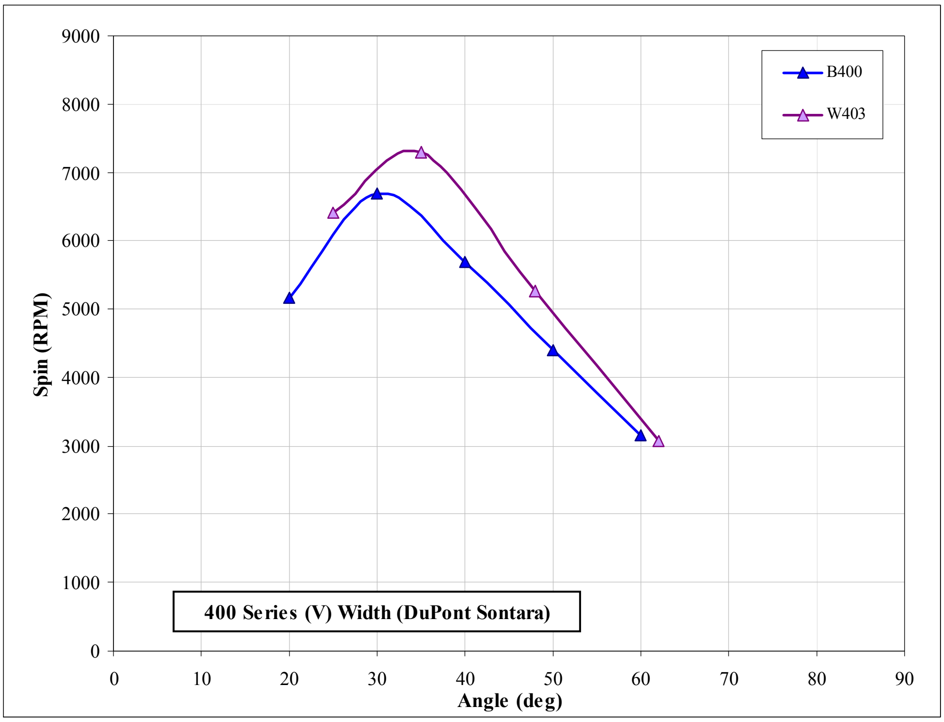


Figure 4.37: Effect of width on spin results for 400 series plates (DuPont Sontara)

As with groove depth, spin increases with width. Once again, thirty five degree impacts with newsprint clearly demonstrate this effect as shown in Figure 4.38.

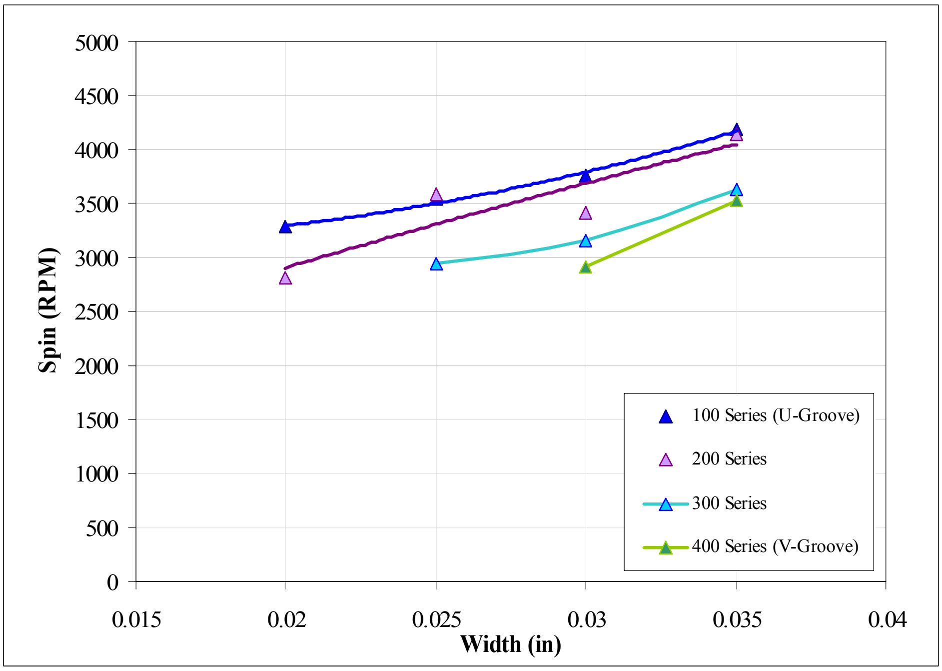


Figure 4.38: Effect of groove width on 35 degree spin results (newsprint)

4.6. Milling (M-series)

A series of plates were milled spanning the range of conformance to 20% over the limit, they include: a grooveless plate, and each of the 4 draught angle base grooves. Milling was varied from approximately 150-250 micro inches and the milling orientation was varied through 3 angles 0°,45°,and 90°.

Table 4.4: M-Series Plate Dimensions

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Milling Angle (deg.)	Ra (micro-inches)
M001	N/A	N/A	N/A	0	100
M101	90	0.030	0.020	0	160
M102	90	0.030	0.020	0	190
M103	90	0.030	0.020	0	265
M104	90	0.030	0.020	90	140
M105	90	0.030	0.020	45	190
M201	75	0.030	0.020	0	110
M202	75	0.030	0.020	0	175
M203	75	0.030	0.020	0	410
M301	65	0.030	0.020	0	140
M302	65	0.030	0.020	0	200
M303	65	0.030	0.020	0	250
M304	65	0.030	0.020	90	215
M305	65	0.030	0.020	45	150
M401	55	0.030	0.020	0	150
M402	55	0.030	0.020	0	200
M403	55	0.030	0.020	0	255
M404	55	0.030	0.020	90	215
M405	55	0.030	0.020	45	250

The effect of milling and milling direction on spin for a grooveless plate and the four groove shapes are plotted in Figures 4.39 through 4.48.

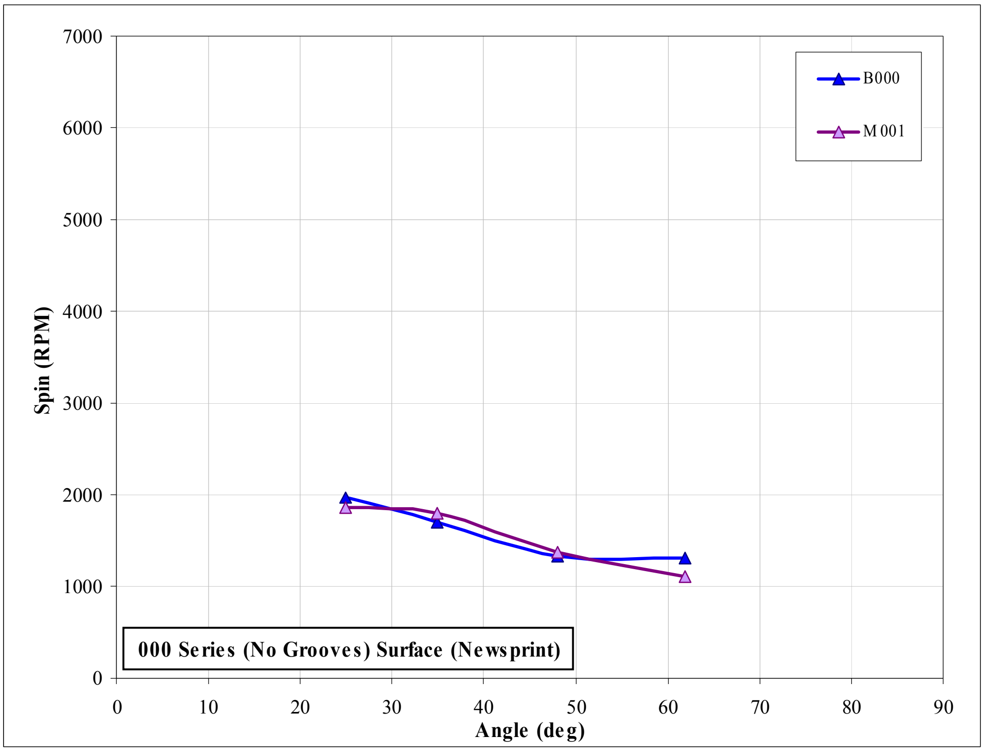


Figure 4.39: Effect of milling on spin results for grooveless plates (newsprint)

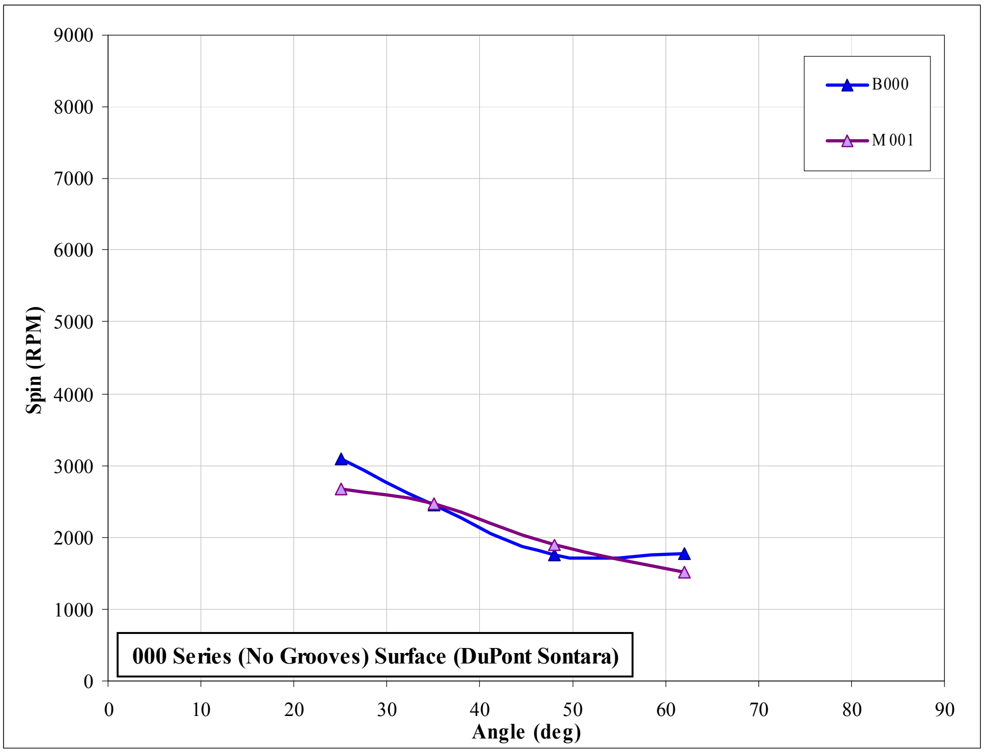


Figure 4.40: Effect of milling on spin results for grooveless plates (DuPont Sontara)

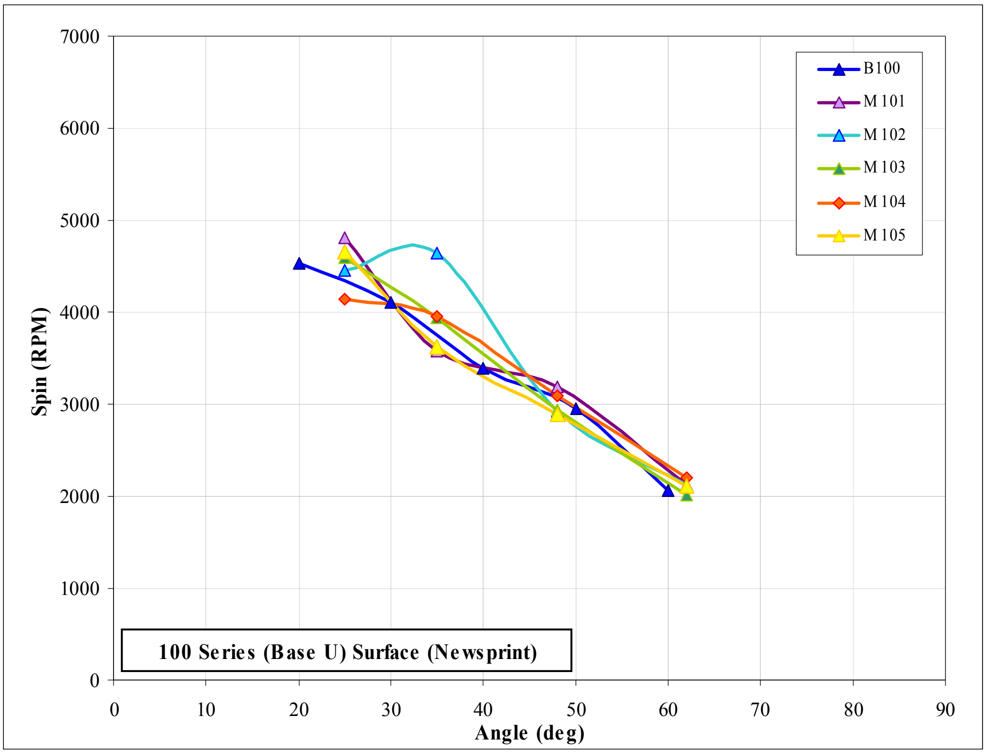


Figure 4.41: Effect of milling on spin results for 100 series plates (newsprint)

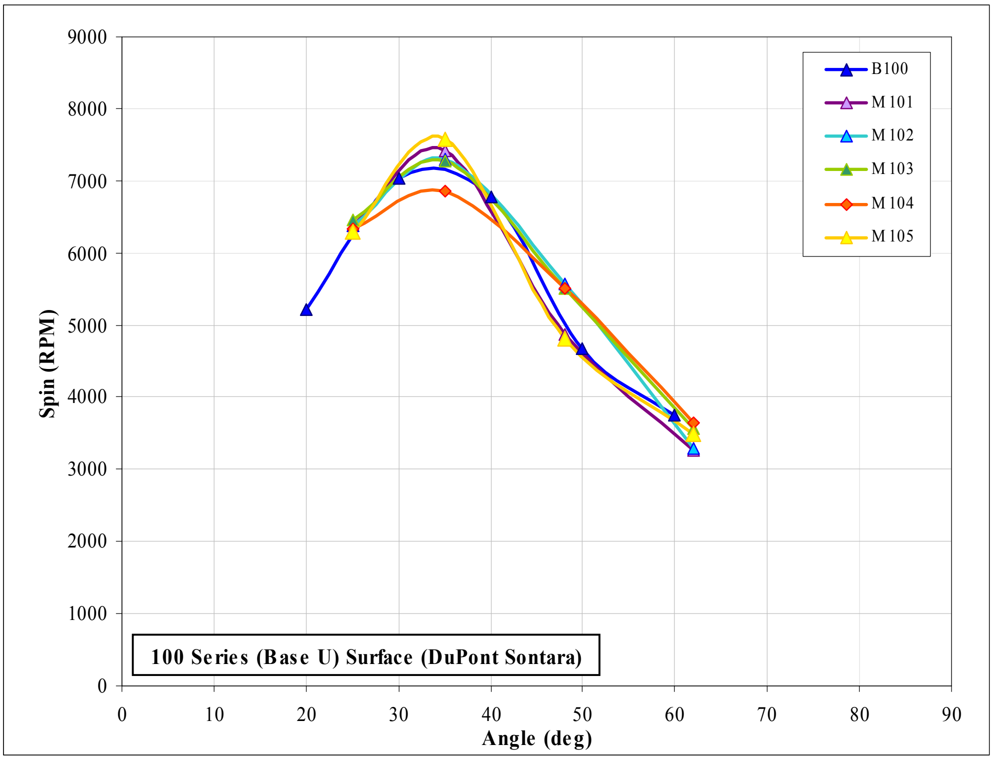


Figure 4.42: Effect of milling on spin results for 100 series plates (DuPont Sontara)

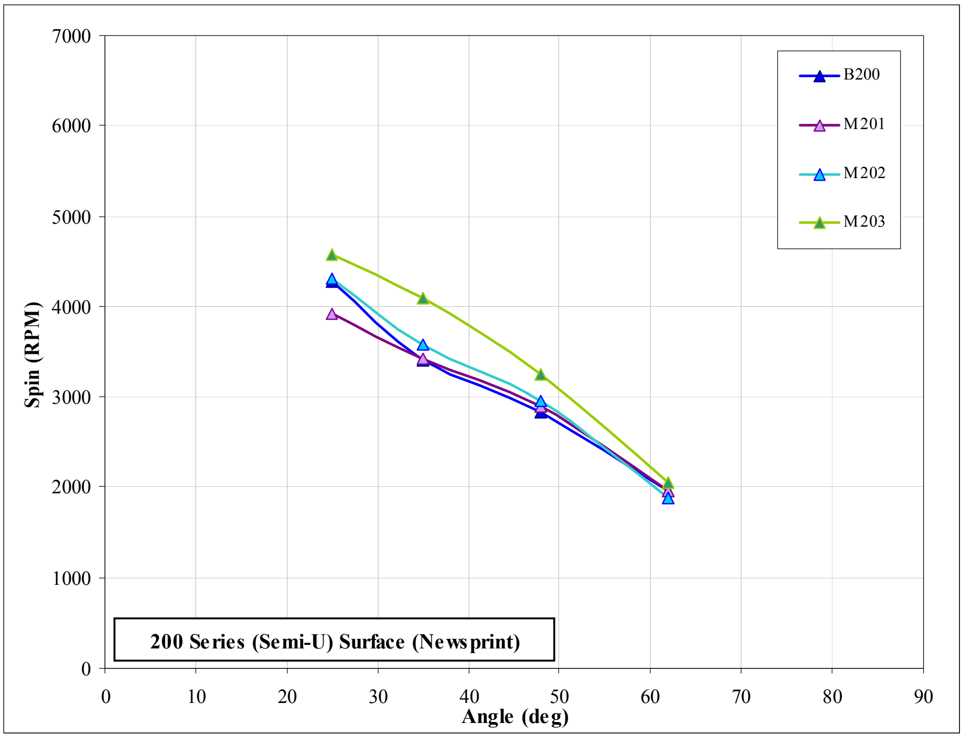


Figure 4.43: Effect of milling on spin results for 200 series plates (newsprint)

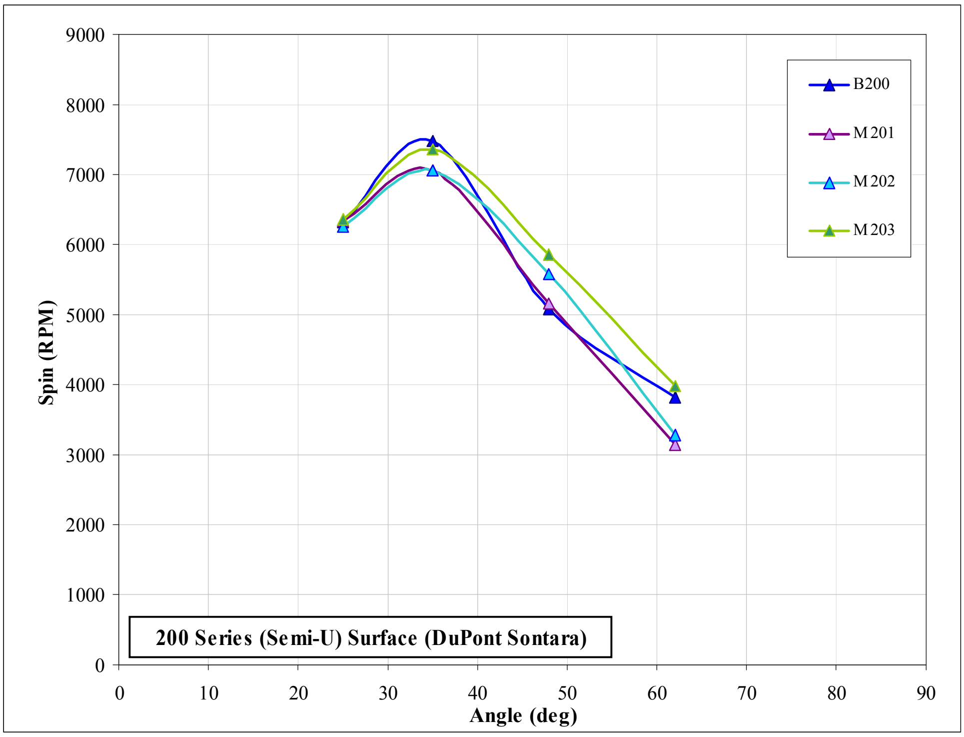


Figure 4.44: Effect of milling on spin results for 200 series plates (DuPont Sontara)

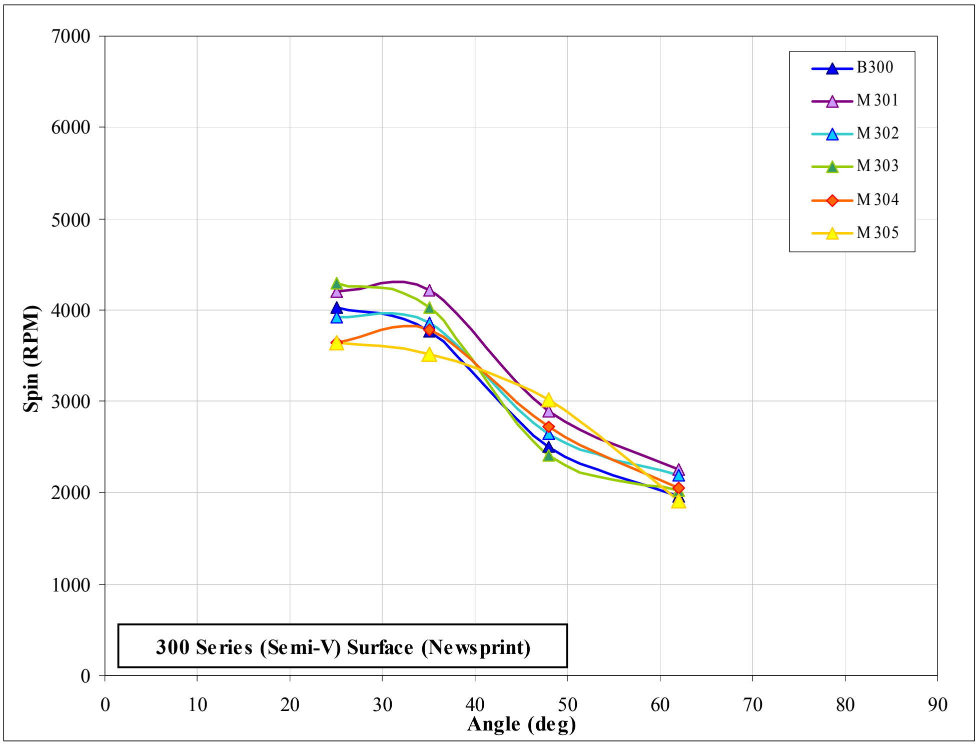


Figure 4.45: Effect of milling on spin results for 300 series plates (newsprint)

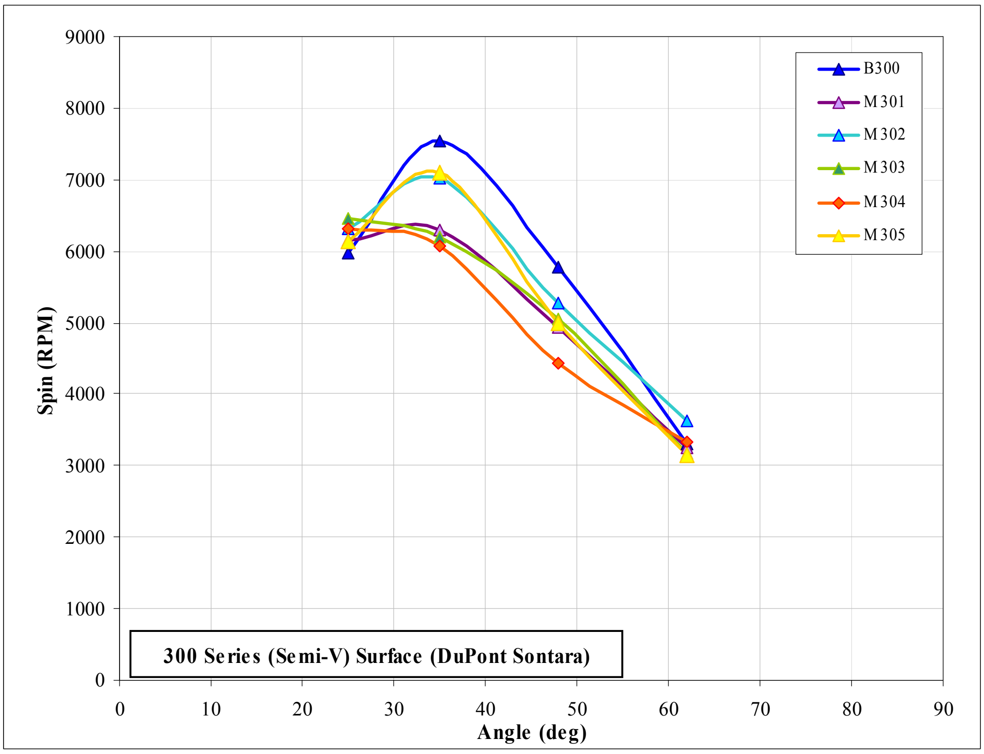


Figure 4.46: Effect of milling on spin results for 300 series plates (DuPont Sontara)

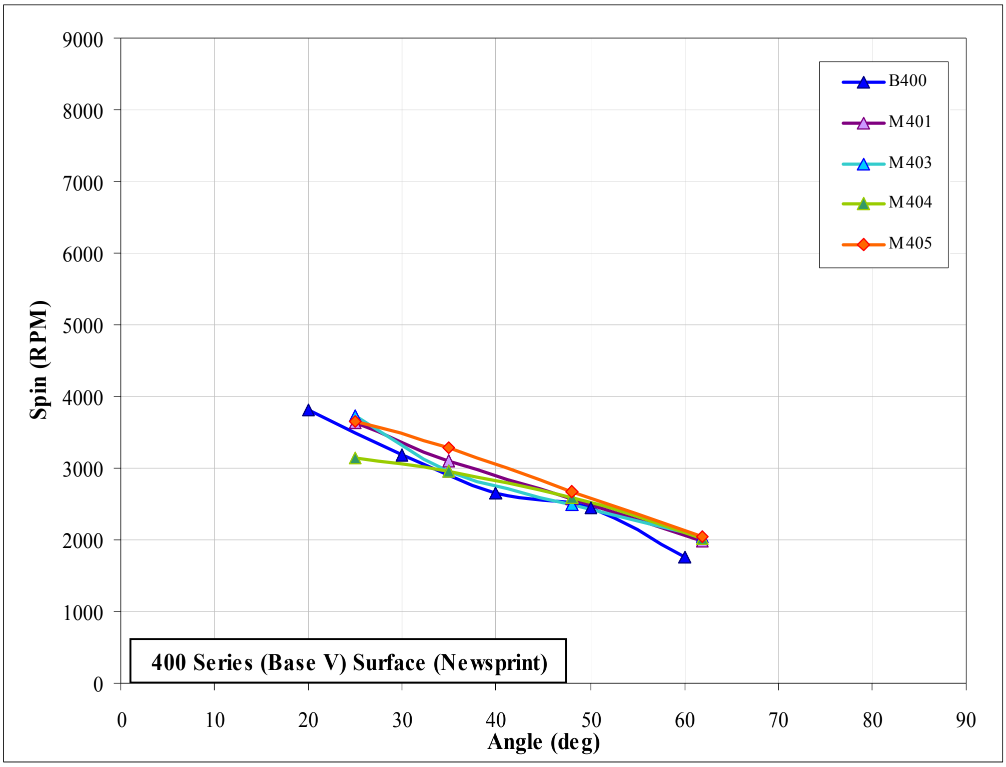


Figure 4.47: Effect of milling on spin results for 400 series plates (newsprint)

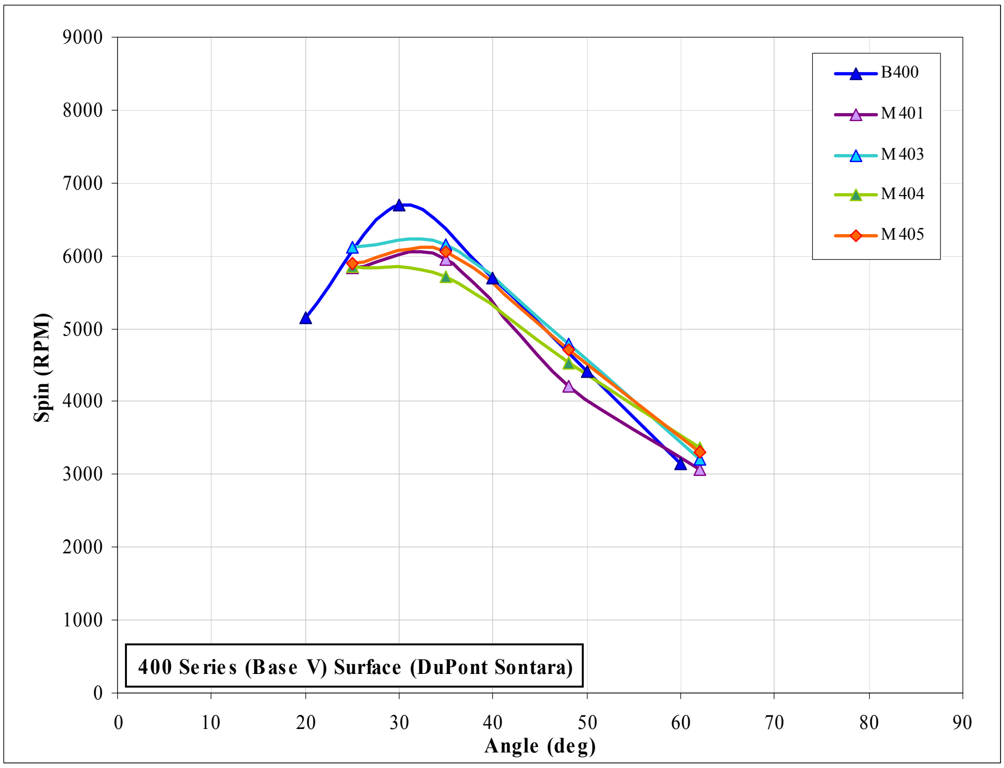


Figure 4.48: Effect of milling on spin results for 400 series plates (DuPont Sontara)

5. Correlation of Phase I Results and Spin Prediction

The first phase of testing isolated each of the groove parameters independently and their effect on spin was tested.

5.1. Correlation of Phase I Results

A linear correlation was developed from the Phase I test results. This correlation was intended to include the following key findings:

- The spin increases as the groove shape changes from V to U
- Decreasing edge radius increases spin
- Increasing edge radius above 0.010-in has limited effect
- Edge radius has a greater effect for large draught angles
- Decreasing spacing increases spin
- Increasing depth increases spin
- Increasing width increases spin

Spin results at thirty five degrees with newsprint were used to relate the groove parameters to spin. Results at other angles provide similar conclusions.

Several different combinations of the design parameters were tested. The most suitable correlation equation form was:

$$\omega_{35^\circ} = X\frac{\left(\theta_{draught} - 45\right)}{R_{edge}} + Y\frac{A}{S} + Z \qquad (5.1)$$

where ω_{35} is the spin for impacts at thirty five degrees with newsprint interface, $\theta_{draught}$ is the groove sidewall draught angle (degrees), R_{edge} is the edge radius (inches), A is the cross-sectional area of the groove (square inches), and S is the pitch of the grooves (inches). X, Y and Z are linear regression coefficients.

The form of Equation (5.1) includes the key findings of the Phase I testing. The first term is most influential for large draught angles and small edge radii. Owing to the numerator, this term gets smaller as the draught angle is reduced. Including the edge radius in the denominator provides some of the non-linearity observed in Figure 4.12. The width and depth have been accommodated through the cross-sectional area term as has the basic groove shape effect on spin. Finally spacing acts to multiply the cross-sectional area. In effect, the second term is the cross-sectional area per unit height of club face.

Equation (5.1) was fit to the data collected in Phase I and the fitted equation is:

$$\omega_{35^\circ} = 0.12\frac{(\theta_{draught} - 55)}{R_{edge}} + 620000\frac{A}{S} + 1130 \qquad (5.2)$$

The measured spin is plotted against the spin predicted by Equation (5.2) in Figure 5.1.

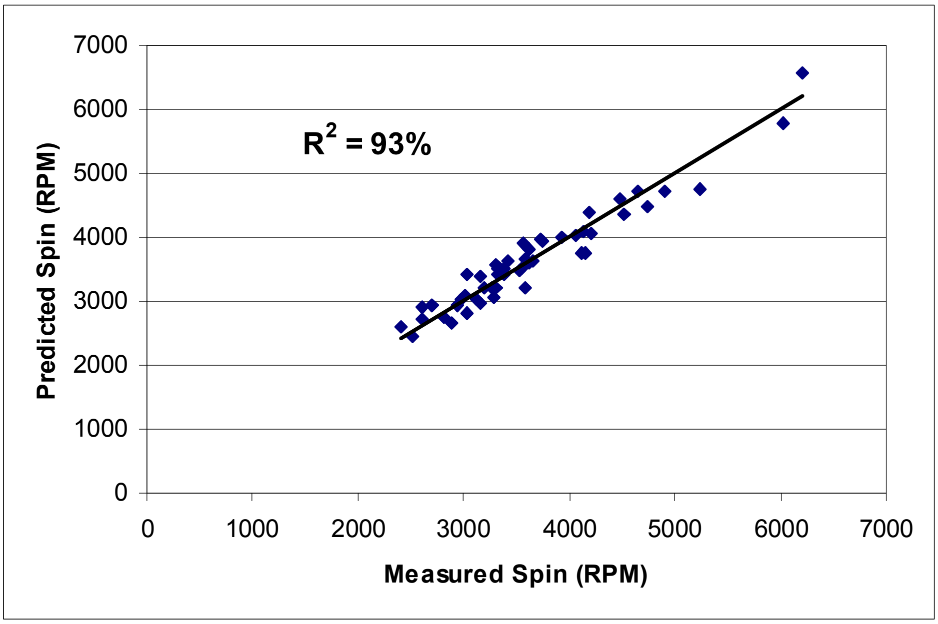


Figure 5.1: Performance of spin/groove parameter correlation (Phase I)

It can be seen in Figure 5.1 that the correlation fits the measured data very well with a coefficient of determination of 93%. It should be noted however that, since the Phase I plates varied only one groove parameter at a time, Equation (5.2) was considered only for guidance and that confirmation of this relation needed verification.

5.2. Phase II Plate Designs

The second phase of this portion of the project was to combine variations in groove parameters with the purpose of reducing the spin performance to that of the V-groove.

Equation 5.2 was used to generate plate designs where multiple groove dimensions were varied simultaneously to achieve spin performance close to that of the V-groove. Twenty five additional plates were manufactured. The specifications for these plates are provided in Appendix A.B.

A few additional plates were also created to study minor topics. These include punch marks and grooves with internal shoulders. The performance of these plates are discussed in Appendix A.D.

5.3. Phase II Testing Results

The plates in Phase II were tested in the same manner as those in Phase I. That is, impacts at 25, 35, 48 and 62 degrees with both newsprint and Sontara grass surrogate materials. Spin results have been tabulated in Appendix A.C. The measured spin at thirty five degrees with newsprint material was compared to the target performance, that of the V-groove plate (B400, green bar). The results are plotted in Figure 5.2. The spin of R102 (groove at the limit of the current conformance standard) is also included in red for reference.

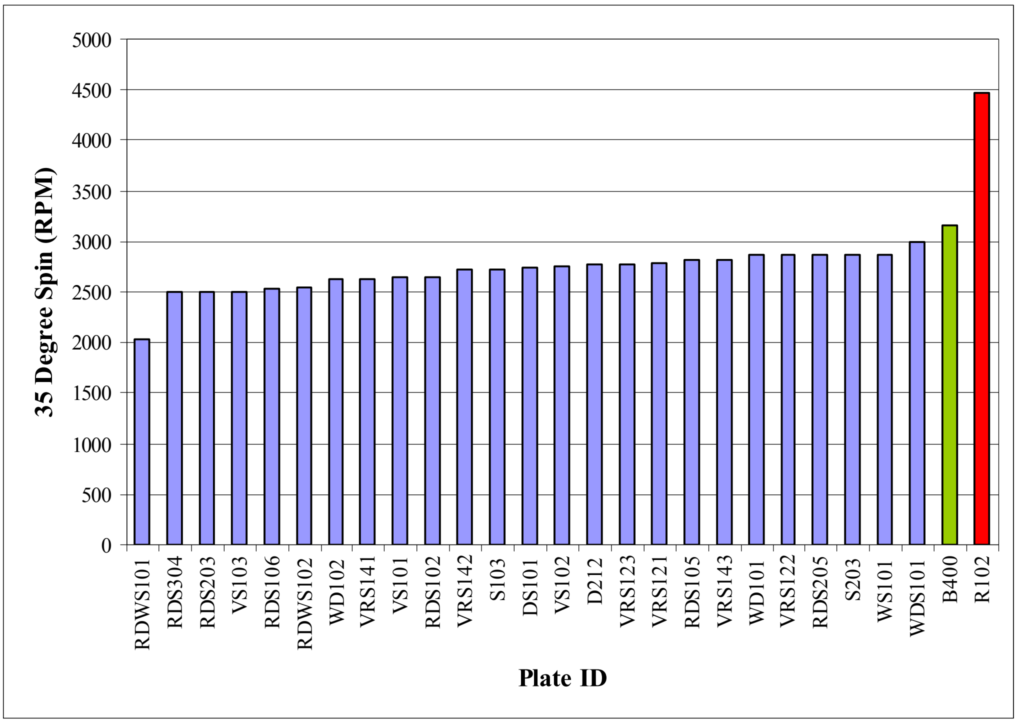


Figure 5.2: Performance of Phase II (V-groove like) plate designs

Two things can be seen in Figure 5.2. First, the Phase II plates somewhat underperformed the target. The average spin of the Phase II designs was 2700 RPM compared to 3200 for the V-groove plate. This indicates that the groove parameters affect spin somewhat differently when modified simultaneously than was predicted by Equation (5.2). However, it can also be seen in Figure 5.2 that the Phase II plates performed similarly to each other indicating that the principle of predicting spin by the groove specification was sound.

5.4. Edge Radius Control

The modern, three-piece, urethane cover ball (U3P) was used for the testing of the Phase I and II plates. However, other ball types have also been considered and tested against a subset of the grooved plates[5]. From this work, it has been found that for edge radii less than 0.010-in, the results are sensitive to ball construction. Therefore, the remainder of this report will focus on those plates with edge radii greater than or equal to 0.010-in.

5.5. Improved Spin Correlation (Phase I and II)

Since only edge radii equal to or greater than 0.010-in are being considered, one term of the correlation equation can be eliminated. For these grooves therefore, it is expected that the spin will be a function of the groove area per unit height of club face only. This is demonstrated in Figures 5.3 and 5.4 for impacts at 35 and 62 degrees respectively. Both plots are for impacts with newsprint material. Superimposed on these plots are red lines indicating the spin and cross-sectional area of a V-groove.

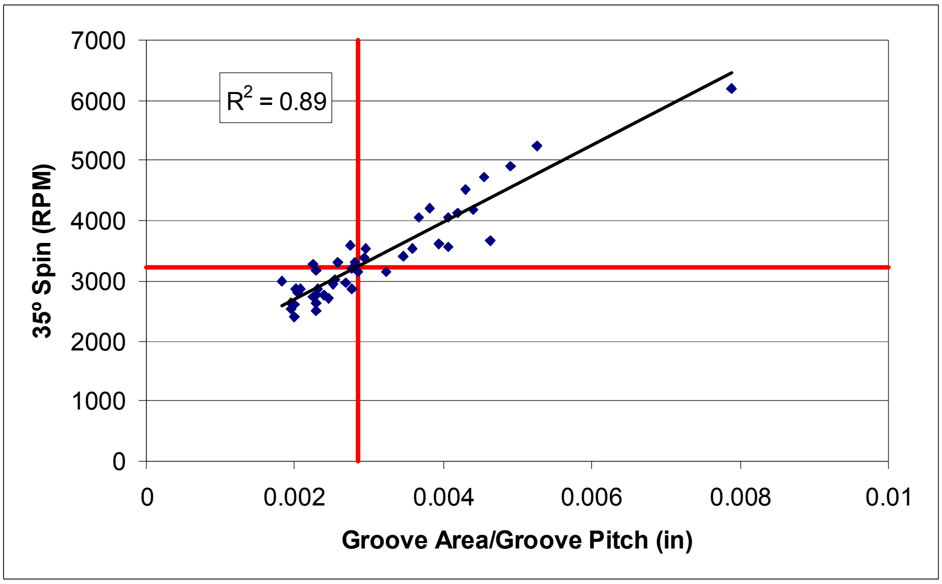


Figure 5.3: Performance of plates for 35 degree impact (R ≥ 0.010-in)

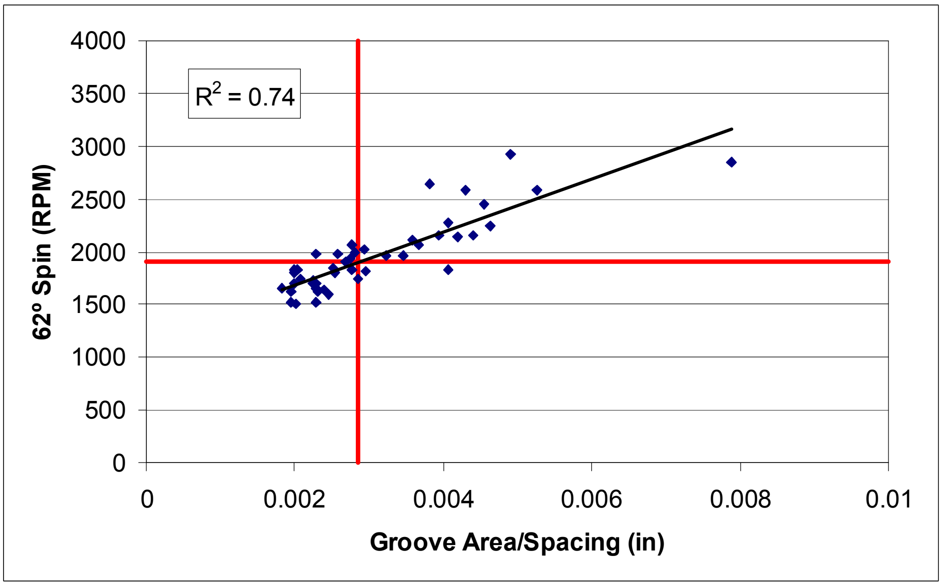


Figure 5.4: Performance of plates for 62 degree impact (R ≥ 0.010-in)

It can be seen in Figures 5.3 and 5.4 that the spin performance is well predicted by the cross-sectional area of the groove divided by the groove spacing (pitch). It should be noted that the data point near 0.008 (D104 plate) does not exhibit undue leverage on the correlation and the coefficient of determination is nearly unchanged with its deletion.

6. CONCLUSIONS

Two sets of grooved test plates were fabricated and tested for their performance with oblique impacts with golf balls. Two interfacial materials were used to simulate the effect of grass on the impact. The first set of plates (Phase I) was designed to vary individual groove design parameters independently. These parameters were groove shape, width, depth, edge sharpness and spacing. Testing of these plates revealed that the total cross-sectional area of the grooves in the impact area (controlled by groove shape, width, depth and spacing) had a direct affect on the resulting spin. Additionally, it was found that the sharpness of the grooves had a large affect when the groove sidewalls were steep. The effect of edge radius diminished as the groove shape transitioned towards a V-groove profile.

The second set of test plates (Phase II) were designed to have the oblique impact performance of the V-groove but without necessarily having a V-groove profile. Groove design parameters were varied simultaneously to achieve this objective. It was found that the expected performance was slightly lower than that of the V-groove based on findings of the Phase I testing. Results from both sets of tests were then combined and it was found that, for plates having an edge radius of 0.010–in or larger, the spin may be estimated from the total cross-sectional area in the impact zone.

7. REFERENCES

1) **Procedure to Study the Effect of Groove Specifications on Launch Conditions**
June 23, 2006 (see Interim Report on Study of Spin Generation, Appendix G, August 7, 2006.)

2) **Identification and Characterization of Experimental Surrogates for Grass**
June 22, 2006 (see Interim Report on Study of Spin Generation, Appendix D, August 7, 2006.)

3) **Fundamental Mechanics of Oblique Impact (Part I: Rigid Body Model)**
USGA Test Centre Report RC/spn2004-01, September 29, 2004

4) **Fundamental Mechanics of Oblique Impact (Part II: Homogeneous Elastic Sphere)**
USGA Test Centre Report RC/spn2005-01, March 3, 2005 (see Interim Report on Study of Spin Generation, Appendix H, August 7, 2006.)

5) **Effect of the Golf Ball on Oblique Impact Testing of Grooved Plates**
(see Second Report on Study of Spin Generation, Appendix B.)

APPENDIX A.A: GROOVE WIDTH MEASUREMENT METHODS

Figure A.1 graphically demonstrates the 30 degree and 45 degree methods used to define groove width of a typical U-groove. Grooves are measured between the two points of tangency created by lines that are 30 degrees (or 45 degrees depending on the method) from the flat land area of the club face.

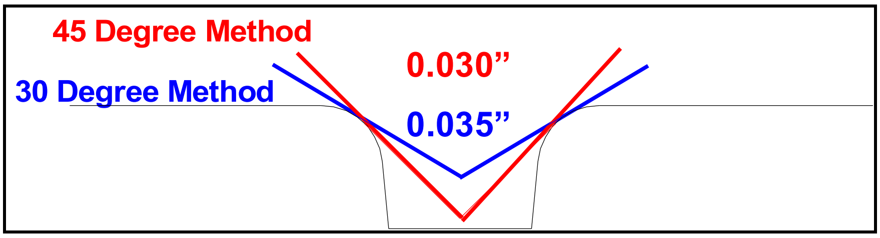


Figure A.1: Groove Width Measurement

Figure A.2 is a plot of groove cross-sectional area vs. tangent degree method. This plot illustrates the sensitivity of groove cross-sectional area to edge radius for a given degree method of measurement. For example: a groove that has a 0.000-in edge radius and measures 0.035-in wide by the 30 degree method has a 40% larger cross-sectional area than a groove that has a 0.020-in edge radius and also measures 0.035-in by the 30 degree method. Choosing to define groove width measurement by the 45 degree method minimises the sensitivity of groove area to edge radius.

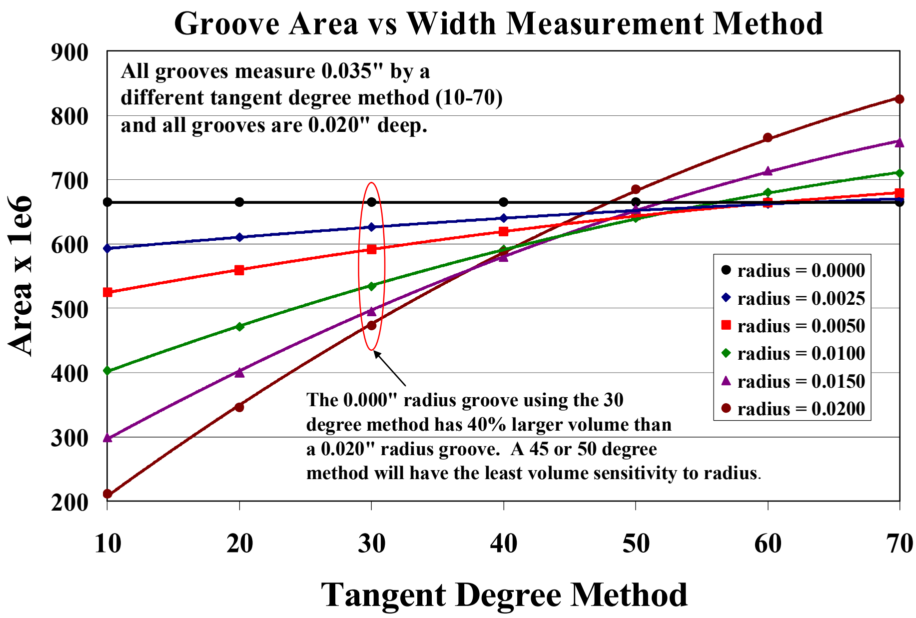


Figure A.2: Groove Cross-sectional Area Sensitivity Edge Radius

APPENDIX A.B: PHASE II TEST PLATE DIMENSIONS

Serial #	Draught Angle (deg)	Width (in)	Depth (in)	Edge Radius (in)	Groove Pitch (in)
S103	90	0.030	0.020	0.010	0.210
S203	75	0.030	0.020	0.010	0.210
D212	75	0.030	0.0125	0.010	0.140
DS101	90	0.030	0.015	0.010	0.175
RDS101	90	0.030	0.015	0.0025	0.210
RDS102	90	0.030	0.010	0.0025	0.210
RDS203	75	0.030	0.010	0.0025	0.175
RDS304	65	0.030	0.0125	0.0025	0.175
RDS105	90	0.030	0.015	0.005	0.175
RDS205	75	0.030	0.015	0.005	0.175
RDS106	90	0.030	0.010	0.005	0.175
RDWS101	90	0.020	0.010	0.0025	0.210
RDWS102	90	0.025	0.0125	0.005	0.175
WS101	90	0.0225	0.020	0.010	0.175
WDS101	90	0.025	0.015	0.010	0.175
WD101	90	0.0225	0.015	0.010	0.140
WD102	90	0.025	0.0125	0.010	0.140
VRS101	90	0.0219	0.020	0.0025	0.245
VRS102	90	0.0259	0.0166	0.0025	0.245
VRS103	90	0.030	0.0143	0.0025	0.245
VRS111	90	0.0219	0.020	0.0025	0.175
VRS112	90	0.0259	0.0166	0.0025	0.175
VRS113	90	0.030	0.0143	0.0025	0.175
VRS121	90	0.020	0.020	0.005	0.175
VRS122	90	0.025	0.0181	0.005	0.175
VRS123	90	0.030	0.0148	0.005	0.175
VS101	90	0.0242	0.020	0.010	0.175
VS102	90	0.0271	0.0173	0.010	0.175
VS103	90	0.030	0.0152	0.010	0.175
VRS141	90	0.0245	0.020	0.015	0.175
VRS142	90	0.0272	0.0172	0.015	0.175
VRS143	90	0.030	0.0147	0.015	0.175

Appendix A.C: Phase II Test Results

Plate	Condition	Angle (deg)	Inbound Speed (ft/s)	Outbound		
				Speed (ft/s)	Angle (deg)	Spin (RPM)
WDS101	Wet NP	25	116.4	94.8	49.8	2664
WDS101	Wet NP	35	110.7	91.0	70.1	2991
WDS101	Wet NP	48	101.3	85.5	98.1	2365
WDS101	Wet NP	62	93.6	82.5	123.8	1656
WDS101	Wet Sontara	25	116.0	116.0	45.1	5961
WDS101	Wet Sontara	35	110.2	110.2	64.2	6257
WDS101	Wet Sontara	48	101.5	101.5	93.6	4674
WDS101	Wet Sontara	62	93.4	93.4	122.6	3282
S203	Wet NP	25	117.4	95.3	48.5	2881
S203	Wet NP	35	110.3	90.8	70.0	2866
S203	Wet NP	48	101.7	86.1	96.6	2352
S203	Wet NP	62	94.0	82.5	124.1	1626
S203	Wet Sontara	25	116.7	90.2	42.5	6028
S203	Wet Sontara	35	110.3	84.5	64.6	6064
S203	Wet Sontara	48	102.0	81.3	95.5	4199
S203	Wet Sontara	62	93.6	78.7	123.2	2718
WD102	Wet NP	25	117.0	95.7	49.0	2718
WD102	Wet NP	35	111.4	92.1	70.4	2628
WD102	Wet NP	48	102.0	87.2	98.0	2242
WD102	Wet NP	62	94.0	83.5	127.4	1518
WD102	Wet Sontara	25	116.7	90.5	43.2	5493
WD102	Wet Sontara	35	110.9	86.5	65.3	5357
WD102	Wet Sontara	48	102.4	82.2	94.0	4255
WD102	Wet Sontara	62	93.7	78.8	124.4	2712
WD101	Wet NP	25	116.4	94.7	49.9	3094
WD101	Wet NP	35	111.3	91.7	69.5	2862
WD101	Wet NP	48	102.0	87.3	96.3	2271
WD101	Wet NP	62	93.8	82.8	124.1	1512
WD101	Wet Sontara	25	116.1	89.3	43.3	5942
WD101	Wet Sontara	35	111.3	84.9	63.3	6419
WD101	Wet Sontara	48	102.7	81.2	93.6	4824
WD101	Wet Sontara	62	93.3	77.7	124.2	3066
D212	Wet NP	25	116.6	95.0	51.0	2672
D212	Wet NP	35	110.3	90.9	69.7	2772
D212	Wet NP	48	102.2	87.6	97.7	2046
D212	Wet NP	62	93.0	82.2	127.0	1632
D212	Wet Sontara	25	116.8	90.2	43.4	5912
D212	Wet Sontara	35	111.2	85.5	64.4	5960
D212	Wet Sontara	48	102.7	82.9	97.7	3882
D212	Wet Sontara	62	92.9	77.8	125.1	2934

Plate	Condition	Angle (deg)	Inbound Speed (ft/s)	Outbound		
				Speed (ft/s)	Angle (deg)	Spin (RPM)
VRS141	Wet NP	25	117.4	95.0	48.6	3046
VRS141	Wet NP	35	111.3	92.1	70.3	2636
VRS141	Wet NP	48	102.8	87.8	96.3	2106
VRS141	Wet NP	62	93.2	82.8	126.7	1350
VRS141	Wet Sontara	25	118.1	90.6	42.5	6023
VRS141	Wet Sontara	35	111.0	85.6	64.9	5689
VRS141	Wet Sontara	48	102.4	82.2	96.9	3990
VRS141	Wet Sontara	62	93.8	79.4	123.8	2568
VRS142	Wet NP	25	117.4	95.6	48.9	2768
VRS142	Wet NP	35	110.2	90.9	70.0	2721
VRS142	Wet NP	48	101.9	87.0	98.0	2076
VRS142	Wet NP	62	94.0	82.9	127.6	1866
VRS142	Wet Sontara	25	117.3	90.4	42.2	6036
VRS142	Wet Sontara	35	110.9	86.2	65.9	5487
VRS142	Wet Sontara	48	102.8	82.5	96.3	4002
VRS142	Wet Sontara	62	93.6	78.5	125.5	3006
VRS143	Wet NP	25	116.9	94.9	48.7	3004
VRS143	Wet NP	35	111.3	92.0	69.4	2816
VRS143	Wet NP	48	101.9	86.7	99.1	2214
VRS143	Wet NP	62	94.0	82.5	125.6	1836
VRS143	Wet Sontara	25	117.7	91.0	42.7	5780
VRS143	Wet Sontara	35	110.9	86.1	65.9	5473
VRS143	Wet Sontara	48	102.2	81.7	96.6	4116
VRS143	Wet Sontara	62	93.9	78.6	123.0	2916
WS101	Wet NP	25	117.1	94.7	48.3	3050
WS101	Wet NP	35	110.0	90.6	69.5	2869
WS101	Wet NP	48	102.4	87.0	98.7	2346
WS101	Wet NP	62	94.2	82.6	125.4	1740
WS101	Wet Sontara	25	117.3	90.2	42.4	6303
WS101	Wet Sontara	35	110.7	83.7	62.5	6947
WS101	Wet Sontara	48	102.6	80.3	94.3	4944
WS101	Wet Sontara	62	94.2	77.9	123.6	3300
RDWS102	Wet NP	25	116.8	94.9	48.6	2838
RDWS102	Wet NP	35	110.3	91.6	71.4	2540
RDWS102	Wet NP	48	101.7	86.9	97.7	2022
RDWS102	Wet NP	62	94.2	83.6	126.4	1614
RDWS102	Wet Sontara	25	116.8	89.9	41.8	6006
RDWS102	Wet Sontara	35	110.6	85.0	64.2	6001
RDWS102	Wet Sontara	48	101.8	81.1	93.9	4038
RDWS102	Wet Sontara	62	93.7	77.9	125.3	3132

Plate	Condition	Angle (deg)	Inbound Speed (ft/s)	Outbound		
				Speed (ft/s)	Angle (deg)	Spin (RPM)
RDS106	Wet NP	25	116.3	95.0	49.0	2716
RDS106	Wet NP	35	110.3	91.4	71.5	2529
RDS106	Wet NP	48	101.9	86.5	96.9	2100
RDS106	Wet NP	62	94.0	82.6	125.1	1662
RDS106	Wet Sontara	25	116.4	90.3	43.0	5558
RDS106	Wet Sontara	35	110.5	86.4	67.3	5047
RDS106	Wet Sontara	48	101.5	82.7	95.0	3564
RDS106	Wet Sontara	62	94.4	79.1	123.0	2880
DS101	Wet NP	25	116.9	94.6	48.1	3237
DS101	Wet NP	35	110.4	91.1	70.3	2734
DS101	Wet NP	48	101.7	86.0	96.5	2274
DS101	Wet NP	62	93.5	82.2	123.9	1734
DS101	Wet Sontara	25	116.7	90.3	42.2	6150
DS101	Wet Sontara	35	110.6	84.2	65.4	6328
DS101	Wet Sontara	48	101.8	81.0	94.1	4350
DS101	Wet Sontara	62	93.1	76.8	122.2	3366
VS101	Wet NP	25	118.0	95.8	48.5	3042
VS101	Wet NP	35	110.7	91.6	70.6	2646
VS101	Wet NP	48	101.5	86.5	95.9	2220
VS101	Wet NP	62	93.3	82.3	125.2	1518
VS101	Wet Sontara	25	117.7	90.2	42.1	6359
VS101	Wet Sontara	35	110.8	83.7	63.7	6690
VS101	Wet Sontara	48	101.7	81.1	94.2	4230
VS101	Wet Sontara	62	93.7	78.1	122.7	2892
VS102	Wet NP	25	117.2	94.9	48.3	3078
VS102	Wet NP	35	110.7	91.7	70.5	2752
VS102	Wet NP	48	102.4	87.5	96.7	2172
VS102	Wet NP	62	93.5	82.2	127.1	1698
VS102	Wet Sontara	25	117.1	89.9	43.1	6170
VS102	Wet Sontara	35	111.0	85.0	65.3	6116
VS102	Wet Sontara	48	102.1	80.5	93.4	4566
VS102	Wet Sontara	62	93.4	77.6	123.7	2988
VS103	Wet NP	25	116.8	94.1	48.1	3199
VS103	Wet NP	35	111.5	93.0	69.8	2506
VS103	Wet NP	48	101.5	86.6	96.5	2124
VS103	Wet NP	62	93.5	82.1	125.5	1656
VS103	Wet Sontara	25	117.4	89.9	42.0	6112
VS103	Wet Sontara	35	111.5	86.6	65.2	5561
VS103	Wet Sontara	48	101.4	81.4	94.4	4038
VS103	Wet Sontara	62	94.1	78.3	124.8	3072

Plate	Condition	Angle (deg)	Inbound Speed (ft/s)	Outbound		
				Speed (ft/s)	Angle (deg)	Spin (RPM)
RDS205	Wet NP	25	117.4	94.8	48.1	3206
RDS205	Wet NP	35	111.2	92.1	69.1	2864
RDS205	Wet NP	48	101.7	86.4	96.4	2322
RDS205	Wet NP	62	93.7	82.3	125.4	1878
RDS205	Wet Sontara	25	117.3	89.9	42.5	6015
RDS205	Wet Sontara	35	111.3	85.2	63.3	6355
RDS205	Wet Sontara	48	101.2	80.6	93.6	4176
RDS205	Wet Sontara	62	93.8	77.8	124.3	3096
RDS304	Wet NP	25	117.1	94.7	47.9	2844
RDS304	Wet NP	35	110.7	92.7	69.2	2496
RDS304	Wet NP	48	102.2	85.5	95.5	2382
RDS304	Wet NP	62	93.6	82.3	124.1	1584
RDS304	Wet Sontara	25	117.4	90.4	42.3	5934
RDS304	Wet Sontara	35	110.4	87.0	65.1	5226
RDS304	Wet Sontara	48	102.0	81.2	93.5	4014
RDS304	Wet Sontara	62	94.0	78.5	122.9	2874
S103	Wet NP	25	117.1	94.8	47.6	3024
S103	Wet NP	35	110.2	92.2	69.0	2724
S103	Wet NP	48	102.6	86.1	95.8	2256
S103	Wet NP	62	93.6	82.1	123.8	1596
S103	Wet Sontara	25	116.8	90.1	41.9	6048
S103	Wet Sontara	35	110.6	86.5	64.3	5922
S103	Wet Sontara	48	102.4	80.4	92.9	4494
S103	Wet Sontara	62	94.5	79.2	123.8	2916
RDS203	Wet NP	25	116.5	94.7	49.2	2490
RDS203	Wet NP	35	110.5	92.9	69.6	2502
RDS203	Wet NP	48	102.9	87.2	96.0	2040
RDS203	Wet NP	62	94.6	83.9	126.1	1590
RDS203	Wet Sontara	25	116.4	90.5	43.4	5568
RDS203	Wet Sontara	35	111.3	89.2	68.3	4380
RDS203	Wet Sontara	48	102.4	81.7	93.8	3936
RDS203	Wet Sontara	62	94.8	79.1	125.5	2982
RDWS101	Wet NP	25	117.1	95.9	50.1	2214
RDWS101	Wet NP	35	110.5	93.6	71.1	2028
RDWS101	Wet NP	48	102.8	87.9	96.8	1758
RDWS101	Wet NP	62	94.7	84.2	127.9	1524
RDWS101	Wet Sontara	25	117.4	91.3	44.2	5466
RDWS101	Wet Sontara	35	111.8	89.7	67.0	4380
RDWS101	Wet Sontara	48	102.8	83.9	95.0	3186
RDWS101	Wet Sontara	62	94.4	80.7	127.1	2466

Plate	Condition	Angle (deg)	Inbound Speed (ft/s)	Outbound		
				Speed (ft/s)	Angle (deg)	Spin (RPM)
VRS121	Wet NP	25	116.8	94.3	48.0	3228
VRS121	Wet NP	35	110.7	92.5	68.8	2796
VRS121	Wet NP	48	102.3	85.8	99.3	2400
VRS121	Wet NP	62	94.8	84.1	127.2	1602
VRS121	Wet Sontara	25	118.1	90.3	42.3	6438
VRS121	Wet Sontara	35	111.8	84.8	61.7	6972
VRS121	Wet Sontara	48	102.6	78.9	94.2	5112
VRS121	Wet Sontara	62	94.6	78.5	125.2	3264
VRS122	Wet NP	25	116.4	93.9	48.6	3336
VRS122	Wet NP	35	111.7	93.4	69.2	2862
VRS122	Wet NP	48	101.6	85.2	97.3	2322
VRS122	Wet NP	62	94.6	83.3	127.9	1782
VRS122	Wet Sontara	25	116.6	89.1	43.6	6222
VRS122	Wet Sontara	35	111.5	85.3	63.4	6564
VRS122	Wet Sontara	48	101.7	77.7	94.1	5424
VRS122	Wet Sontara	62	94.3	78.1	126.0	3258
VRS123	Wet NP	25	116.7	94.1	48.6	3408
VRS123	Wet NP	35	111.4	92.9	69.9	2772
VRS123	Wet NP	48	101.3	85.0	97.5	2340
VRS123	Wet NP	62	94.4	82.9	124.2	1692
VRS123	Wet Sontara	25	117.5	90.0	44.4	6132
VRS123	Wet Sontara	35	111.4	85.9	64.9	6120
VRS123	Wet Sontara	48	101.9	78.6	93.9	5100
VRS123	Wet Sontara	62	93.6	77.6	122.9	3000
RDS105	Wet NP	25	116.9	94.3	47.1	3354
RDS105	Wet NP	35	111.4	92.9	70.3	2814
RDS105	Wet NP	48	101.7	84.9	96.4	2346
RDS105	Wet NP	62	94.8	83.4	124.9	1668
RDS105	Wet Sontara	25	117.1	90.1	41.4	6126
RDS105	Wet Sontara	35	111.1	86.0	64.8	5904
RDS105	Wet Sontara	48	102.3	79.8	94.9	4752
RDS105	Wet Sontara	62	94.7	77.8	123.0	3528
RDS102	Wet NP	25	116.0	94.1	49.0	2736
RDS102	Wet NP	35	110.9	92.4	71.0	2652
RDS102	Wet NP	48	102.1	85.3	95.5	2436
RDS102	Wet NP	62	93.3	81.3	124.7	1740
RDS102	Wet Sontara	25	116.7	90.6	43.1	5478
RDS102	Wet Sontara	35	110.7	86.5	65.6	5400
RDS102	Wet Sontara	48	101.8	80.9	93.8	4128
RDS102	Wet Sontara	62	93.1	77.5	123.1	3144

Plate	Condition	Angle (deg)	Inbound Speed (ft/s)	Outbound		
				Speed (ft/s)	Angle (deg)	Spin (RPM)
VRS101	Wet NP	25	117.1	95.1	48.1	2892
VRS101	Wet NP	35	110.4	91.9	69.3	2826
VRS101	Wet NP	48	101.3	85.8	95.7	2436
VRS101	Wet NP	62	93.2	81.7	124.3	1674
VRS101	Wet Sontara	25	116.6	90.1	41.7	6126
VRS101	Wet Sontara	35	110.6	85.5	63.3	6084
VRS101	Wet Sontara	48	102.0	80.8	92.7	4500
VRS101	Wet Sontara	62	93.5	78.0	123.8	2892
VRS102	Wet NP	25	116.9	94.6	47.6	2994
VRS102	Wet NP	35	111.5	93.4	70.4	2436
VRS102	Wet NP	48	102.7	86.7	97.0	2280
VRS102	Wet NP	62	93.9	82.2	124.7	1770
VRS102	Wet Sontara	25	116.9	90.0	41.9	6066
VRS102	Wet Sontara	35	111.3	86.9	65.4	5472
VRS102	Wet Sontara	48	101.2	80.5	93.0	4308
VRS102	Wet Sontara	62	94.0	78.0	123.2	3090
VRS103	Wet NP	25	117.2	95.0	50.0	2844
VRS103	Wet NP	35	110.9	92.5	69.5	2616
VRS103	Wet NP	48	102.3	86.5	96.1	2268
VRS103	Wet NP	62	93.4	82.4	124.8	1758
VRS103	Wet Sontara	25	116.9	90.4	43.3	5808
VRS103	Wet Sontara	35	110.8	86.4	64.5	5736
VRS103	Wet Sontara	48	102.5	81.3	93.0	4452
VRS103	Wet Sontara	62	93.9	78.1	123.2	3036
RDS101	Wet NP	25	117.4	92.5	47.1	4404
RDS101	Wet NP	35	111.1	91.0	67.5	3732
RDS101	Wet NP	48	102.3	83.8	93.9	3354
RDS101	Wet NP	62	93.9	80.1	123.7	2406
RDS101	Wet Sontara	25	116.5	89.5	43.5	6240
RDS101	Wet Sontara	35	111.0	84.1	62.4	6954
RDS101	Wet Sontara	48	101.8	76.7	90.1	6192
RDS101	Wet Sontara	62	93.6	74.9	122.3	4128
VRS111	Wet NP	25	116.7	93.5	47.3	3630
VRS111	Wet NP	35	110.8	91.6	70.5	3036
VRS111	Wet NP	48	100.9	84.8	95.3	2388
VRS111	Wet NP	62	94.2	82.3	124.6	1812
VRS111	Wet Sontara	25	116.2	89.4	42.0	6330
VRS111	Wet Sontara	35	110.8	83.6	61.4	7344
VRS111	Wet Sontara	48	102.0	77.5	90.5	5814
VRS111	Wet Sontara	62	93.9	76.7	123.1	3492

Plate	Condition	Angle (deg)	Inbound Speed (ft/s)	Outbound		
				Speed (ft/s)	Angle (deg)	Spin (RPM)
VRS112	Wet NP	25	117.2	94.1	46.7	3456
VRS112	Wet NP	35	111.2	91.7	68.2	3210
VRS112	Wet NP	48	101.7	86.0	95.1	2412
VRS112	Wet NP	62	94.1	82.0	125.1	1842
VRS112	Wet Sontara	25	116.7	89.0	42.5	6348
VRS112	Wet Sontara	35	111.7	83.7	60.3	7584
VRS112	Wet Sontara	48	101.2	76.8	90.1	5928
VRS112	Wet Sontara	62	94.4	76.8	122.7	3636
VRS113	Wet NP	25	116.6	93.3	48.7	3972
VRS113	Wet NP	35	111.0	91.5	68.3	3468
VRS113	Wet NP	48	102.9	85.3	94.9	2856
VRS113	Wet NP	62	94.7	82.1	125.1	2130
VRS113	Wet Sontara	25	117.1	90.1	41.4	6228
VRS113	Wet Sontara	35	111.2	85.1	62.2	6660
VRS113	Wet Sontara	48	102.1	76.6	89.3	6366
VRS113	Wet Sontara	62	94.2	77.3	123.3	3384

APPENDIX A.D: OTHER PLATE TYPES

Punchmarks

Two plates were fabricated with punchmarks in the impact area rather than grooves. The dimensions of the punchmarks are given in Table D.1. P102 is designed to conform to the current punchmark specification. P103 is designed to conform to the current groove specification.

Table D.1: Punchmark Plate Dimensions

Serial #	Diameter (in)	Separation (in)	Depth (in)	45° Chamfer (in)
P102	0.075	0.168	0.040	0.010
P103	0.035	0.140	0.02	Sharp

The spin performance test results for the newsprint grass surrogate material are given in Figure D.1. Also included in Figure D.1 are U and V groove as well as grooveless plates for comparison.

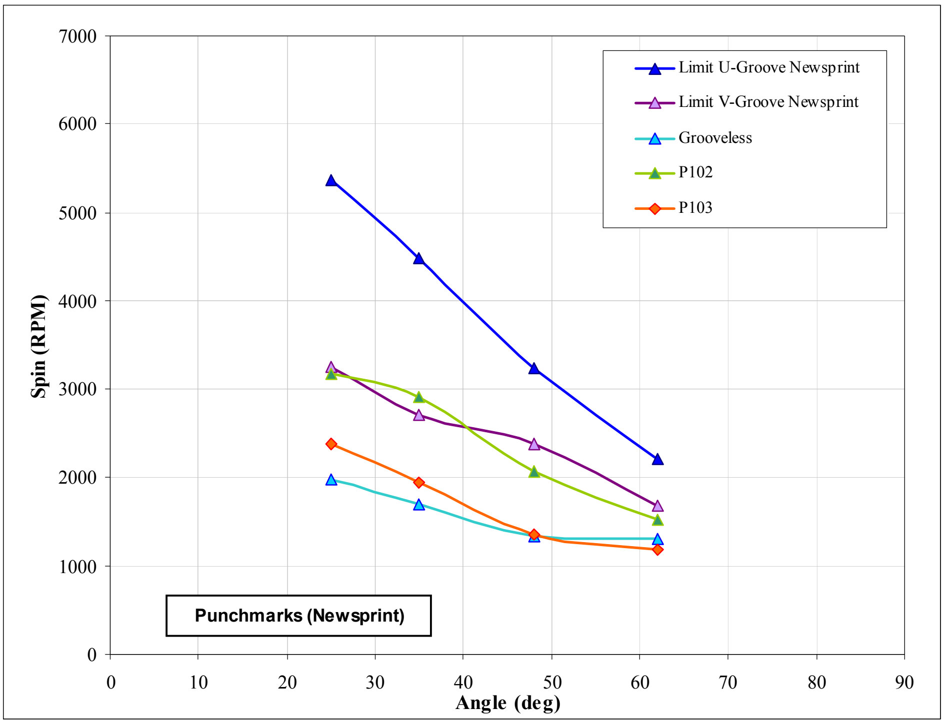


Figure D.1: Spin performance of punchmark plates

It can be seen in Figure D.1 that a plate with punchmarks that conform to the current standard perform very similar to the V-groove plate. It should be noted that the edges of these punchmarks were relieved with a forty five degree chamfer. The smaller punchmarks perform almost the same as a grooveless plate (even with sharp edges).

INTERNAL SHOULDERED GROOVES

Two groove patterns were generated with internal shoulders. These grooves are shown in Figure D.2 and their dimensions are given in Table D.2.

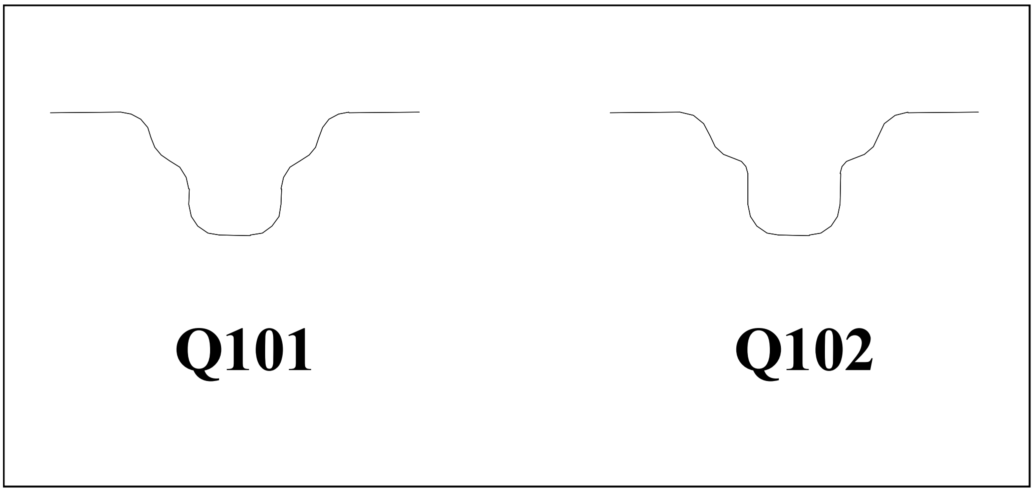


Figure D.2: Internal shouldered grooves

Table D.2: Internal Shoulder Groove Dimensions

Serial #	Edge Radius (in)	Internal Shoulder Radius (in)	Width (in)	Depth (in)	Groove Pitch (in)	Cross-sectional Area* (in^2)
Q101	0.005	0.005	0.035	0.020	0.140	0.0004
Q102	0.005	0.0025	0.035	0.020	0.140	0.0004

* for reference, the cross-sectional area of the V-groove is 0.0004 and the U-groove is 0.0054

The results of the oblique impact tests for both the newsprint and Sontara interface material are shown in Figures D.3 and D.4.

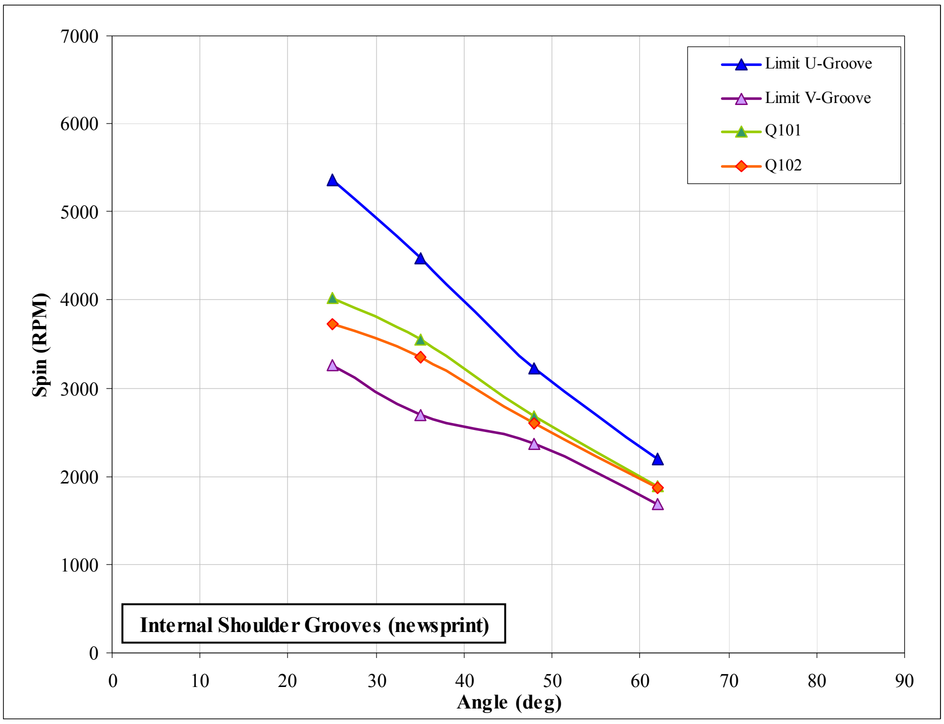


Figure D.3: Spin performance of internal shoulder grooves (newsprint)

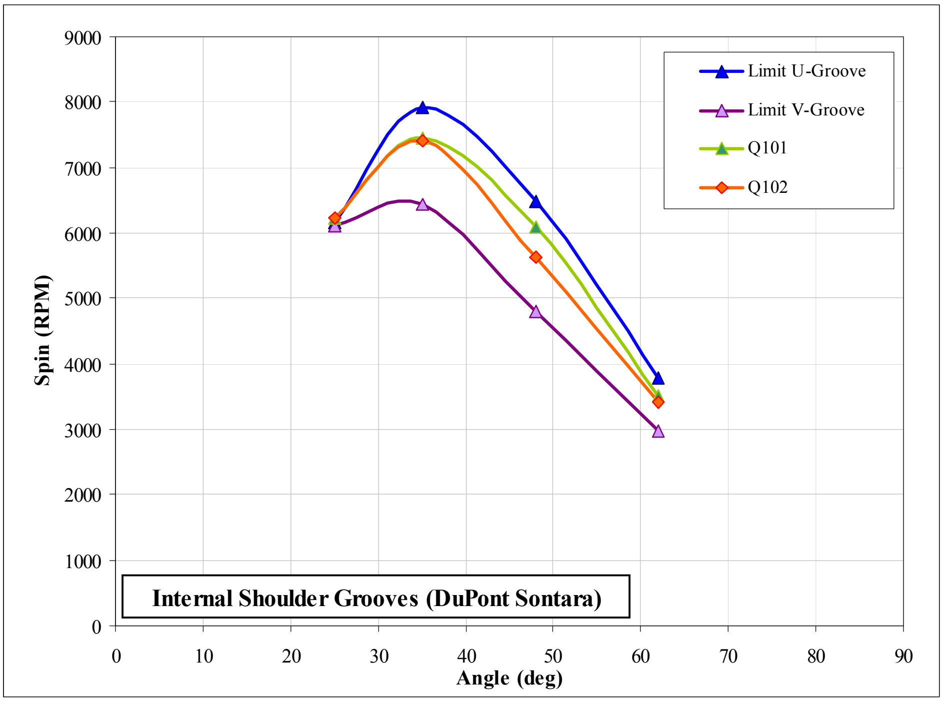


Figure D.4: Spin performance of internal shoulder grooves (DuPont Sontara)

It can be seen in Figures D.3 and D.4 that the grooves do not perform as well as the limit U-groove even though the Q101 and Q102 both have edge radii of 0.005–in, the same as the limit U-groove. This reduction in performance may be attributable to the reduced cross-sectional area of the internal shoulder grooves.

Appendix B

Effect of the Golf Ball on Oblique Impact Testing of Grooved Plates

Dec 18, 2006

1. Summary

The role that the golf ball plays in the spin performance with various groove shapes and edge sharpness has been considered. It has been shown, in the presence of an interfacial material simulating grass, that groove shape and edge sharpness have little or no effect on the spin of a Surlyn covered ball. Furthermore, it has also been shown that the edge sharpness affects two urethane covered balls differently.

2. Test Methodology

Previous testing has revealed that for some groove profiles, the sharpness of the groove can increase the spin from an oblique impact in the presence of an interfacial material[1]. It has also been observed that this effect depends strongly on the construction of the golf ball. Specifically, it has been observed that two similar urethane covered balls performed differently on grooves with small edge radii (sharp groove edges). To that end, a series of oblique impact tests has been conducted to quantify this interdependent relationship.

Plates having groove edge radii of 0.005-in and 0.010-in and a range of draught angles from ninety degrees (U-groove) to fifty five degrees (V-groove) were tested. The two most shallow groove shapes, sixty five and fifty five degrees, were also tested with edge radii of 0.0025-in. Three ball types were used. A three-piece, urethane covered ball (referred to as U3P), a similar, four piece urethane covered ball (U4P) and a two piece Surlyn™ (S2P) covered ball. Impacts were recorded at 25, 35, 48 and 62 degrees according to a standardised oblique impact test procedure[2]. Wetted newsprint was used for the interfacial material.

3. RESULTS

3.1. Three-piece Urethane Cover Ball (U3P)

The results for the three-piece, urethane covered ball (U3P) are given in Figures 1 through 4 for angles 25, 35, 48 and 62 degrees respectively.

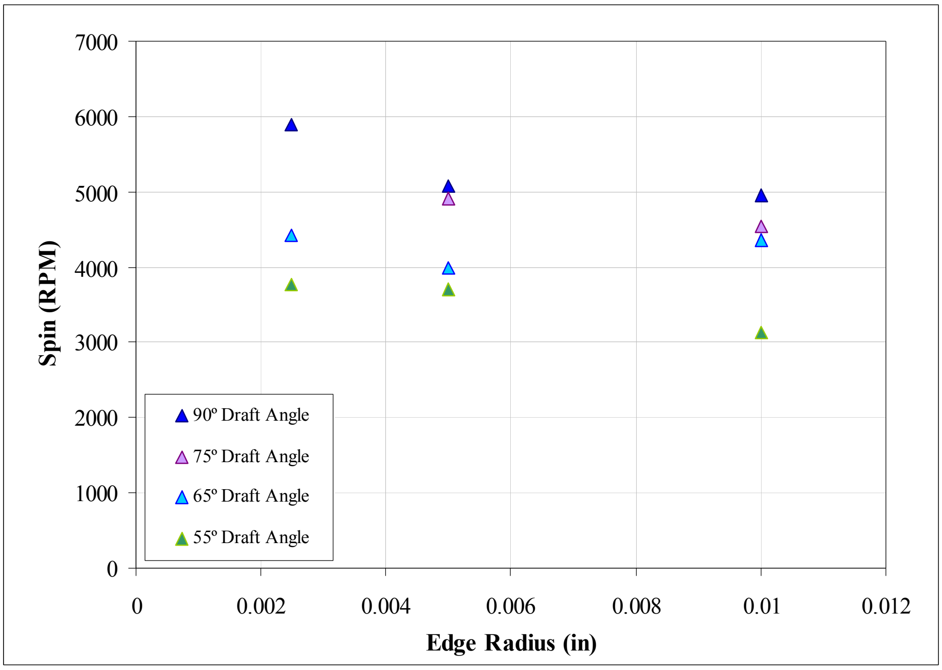


Figure 1: Three-piece urethane ball (U3P), 25 degree impact

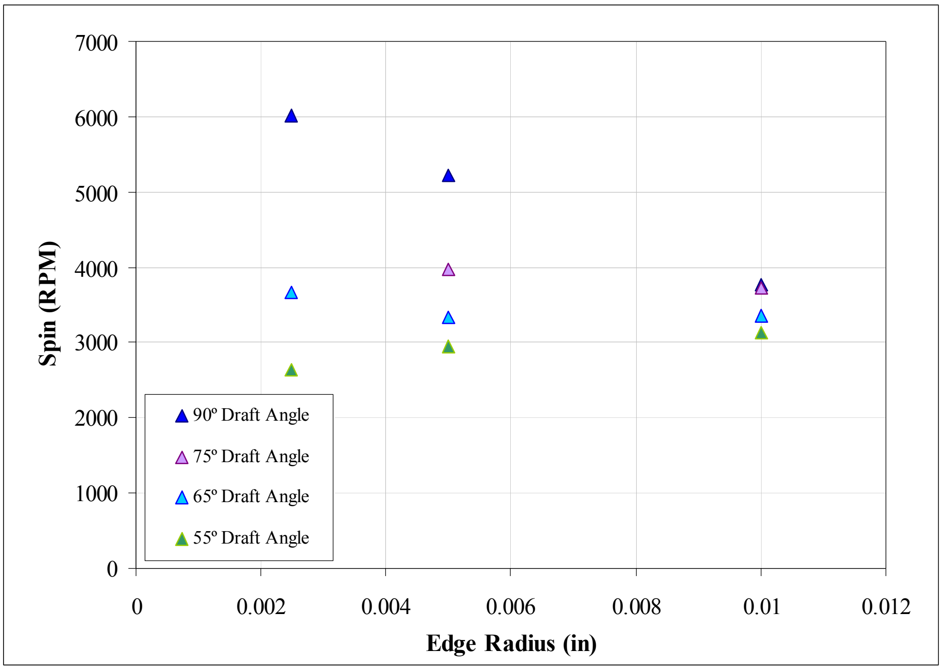


Figure 2: Three-piece urethane ball (U3P), 35 degree impact

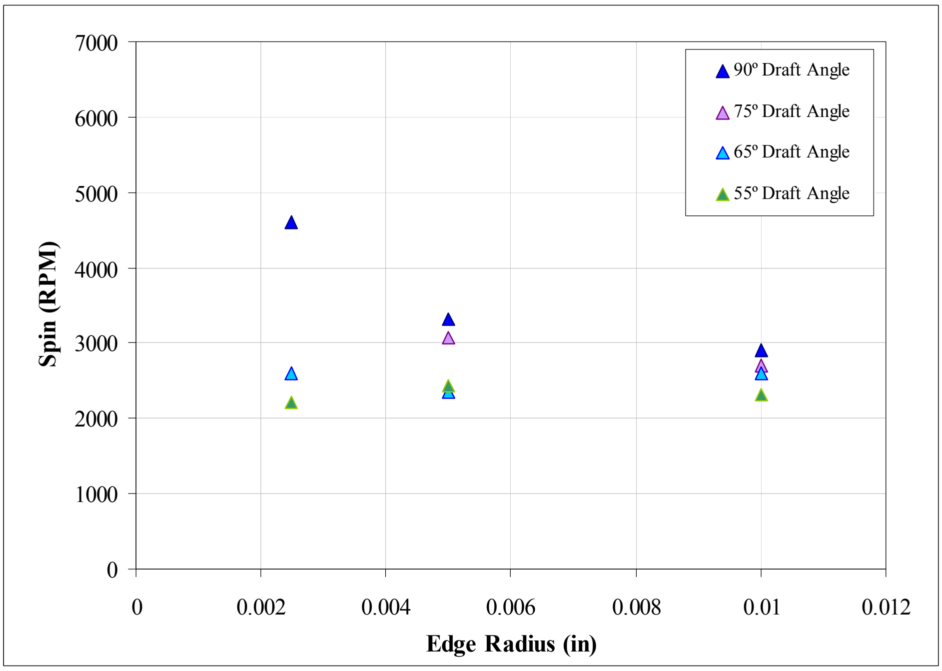


Figure 3: Three-piece urethane ball (U3P), 48 degree impact

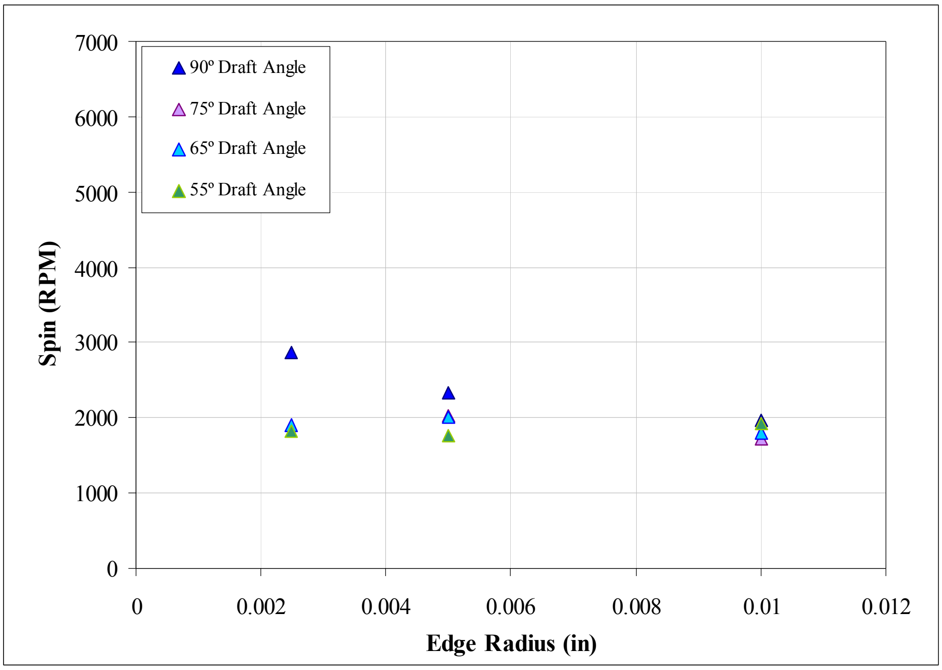


Figure 4: Three-piece urethane ball (U3P), 62 degree impact

It can be seen in Figures 1 through 4 that at the largest draught angle of ninety degrees (U-groove), the effect of edge radius on increasing spin is pronounced at all angles. Edge radius still appears to consistently influence spin at a draught angle of seventy five degrees. However at even lower angles, sixty five and fifty five (V-groove), edge radius does not play a significant role in increasing spin.

3.2. Four Piece Urethane Cover Ball (U4P)

The results for the four piece urethane covered ball (U4P) are given in Figures 5 through 8 for angles 25, 35, 48 and 62 degrees respectively.

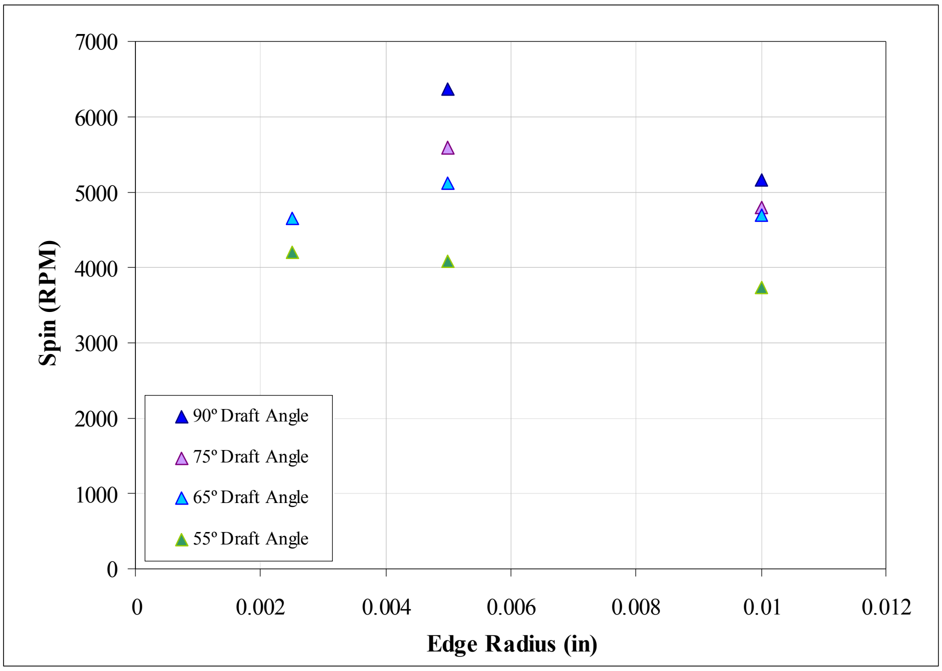


Figure 5: Four piece urethane ball (U4P), 25 degree impact

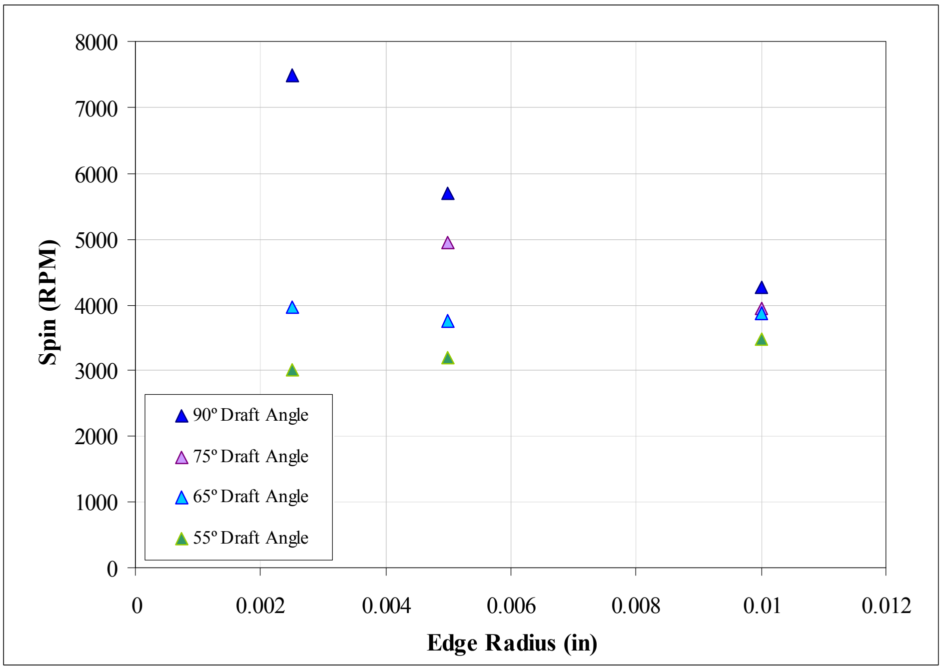


Figure 6: Four piece urethane ball (U4P), 35 degree impact

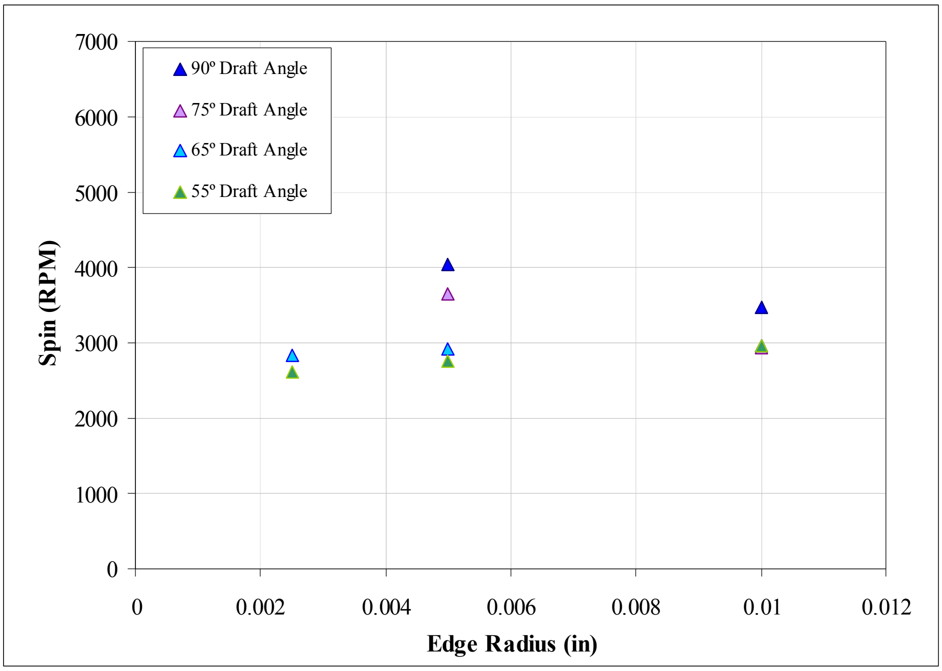


Figure 7: Four piece urethane ball (U4P), 48 degree impact

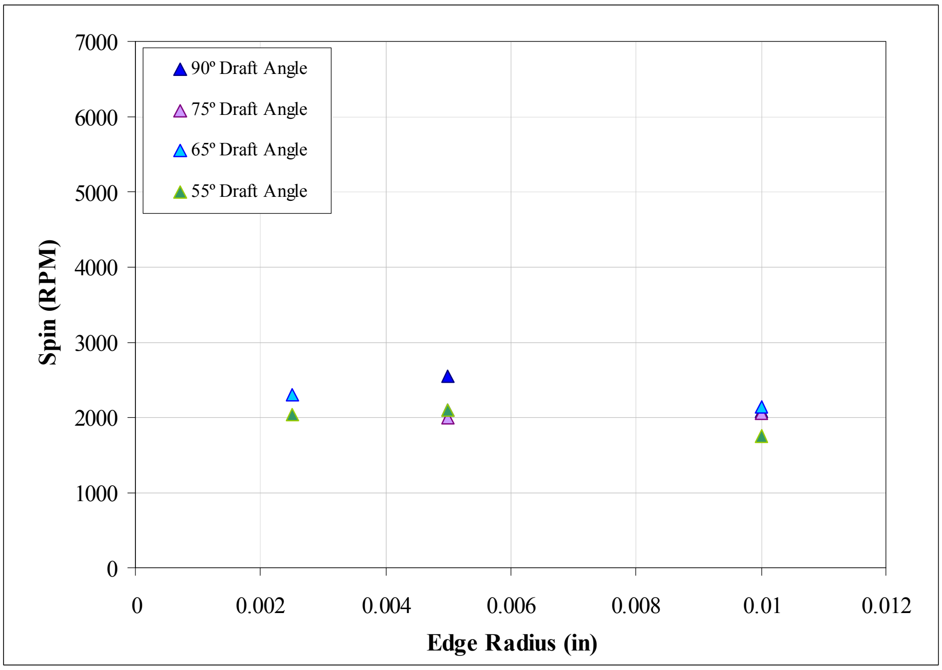


Figure 8: Four piece urethane ball (U4P), 62 degree impact

Similar to the U3P ball, the effect of edge radius on spin is most pronounced for the ninety degree draught angle. For this ball, the edge radius strongly affects the spin at the seventy five degree draught angle as well. As with the U3P ball, the spin at sixty five and fifty five degree draught angles are not appreciably affected by edge radius. Finally, at the highest impact angle (sixty two degrees), neither the edge radius, nor the groove shape appear to affect spin appreciably.

3.3. Two Piece Surlyn Cover Ball (S2P)

The results for the two piece Surlyn cover ball (S2P) are given in Figures 9 through 12 for angles 25, 35, 48 and 62 degrees respectively.

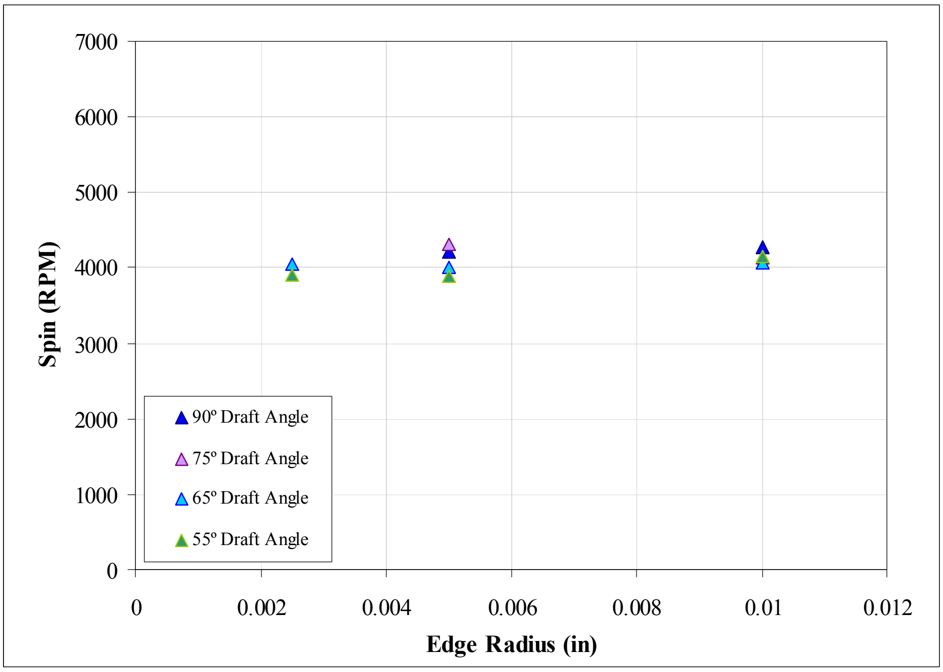


Figure 9: Two piece Surlyn cover ball (S2P), 25 degree impact

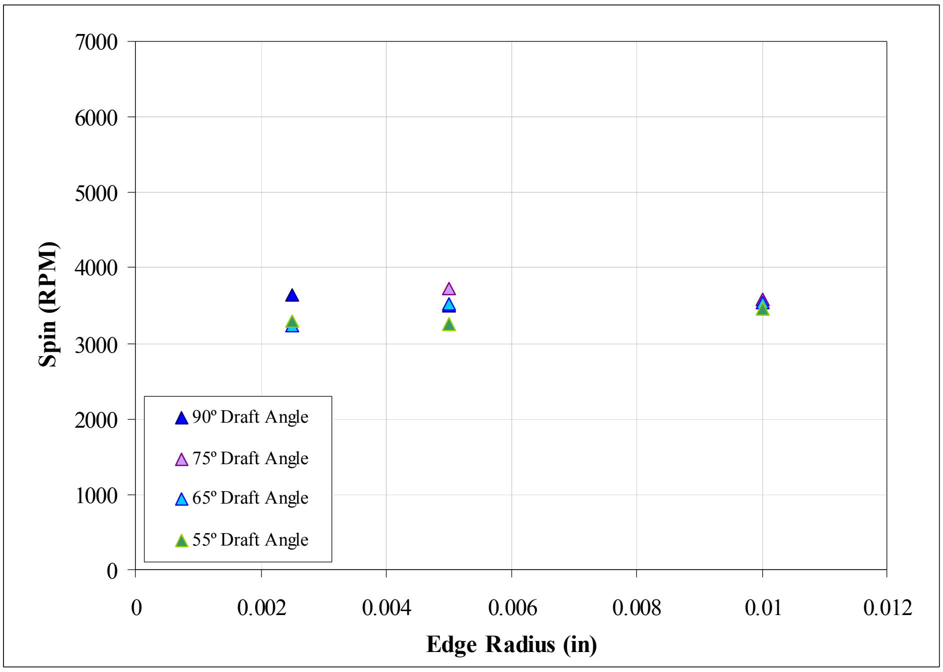


Figure 10: Two piece Surlyn cover ball (S2P), 35 degree impact

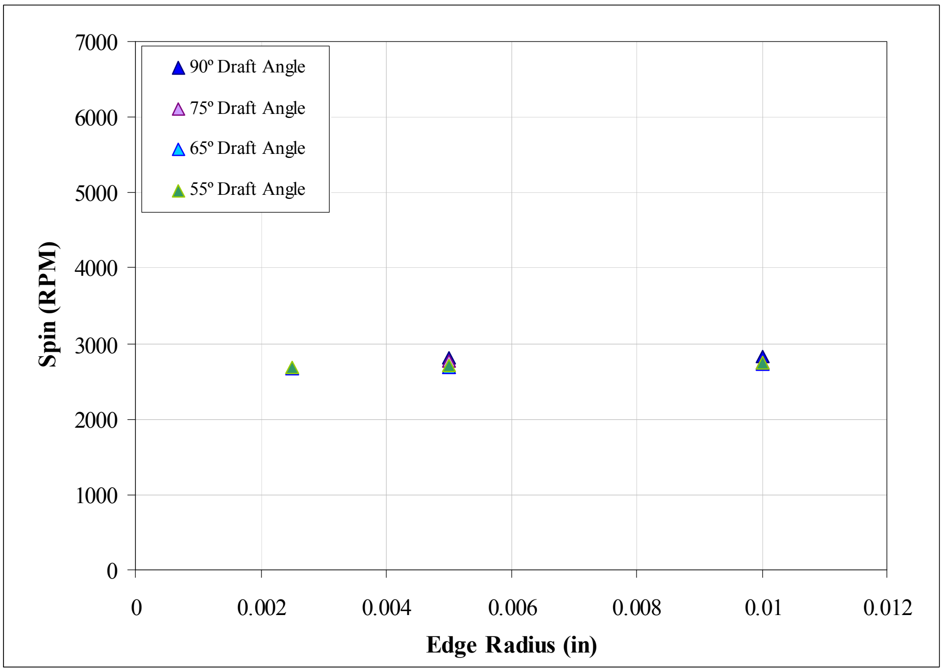


Figure 11: Two piece Surlyn cover ball (S2P), 48 degree impact

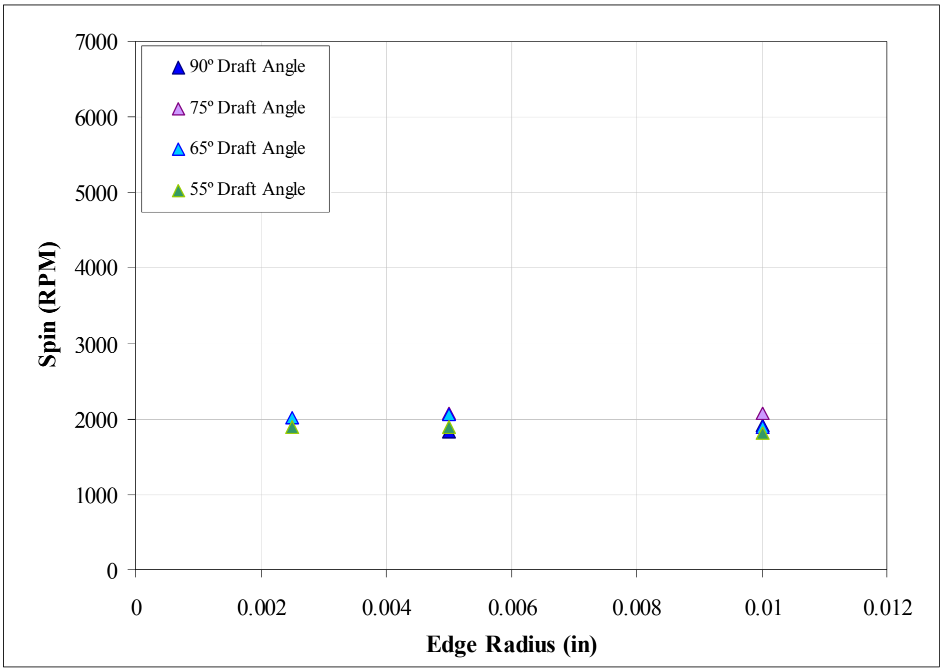


Figure 12: Two piece Surlyn cover ball (S2P), 62 degree impact

It can be seen in Figures 8 through 12 that neither the edge radius nor the groove shape appears to influence the spin at all.

4. Comparison of Effect of Edge Radius on Balls

As has been seen in prior testing, the results for impacts at thirty five degrees best demonstrate the effect of that edge radius has on the different balls. Similar conclusions may be reached at the other angles. Figure 13 compares the effect of edge radius on the U and V grooves for the three balls tested.

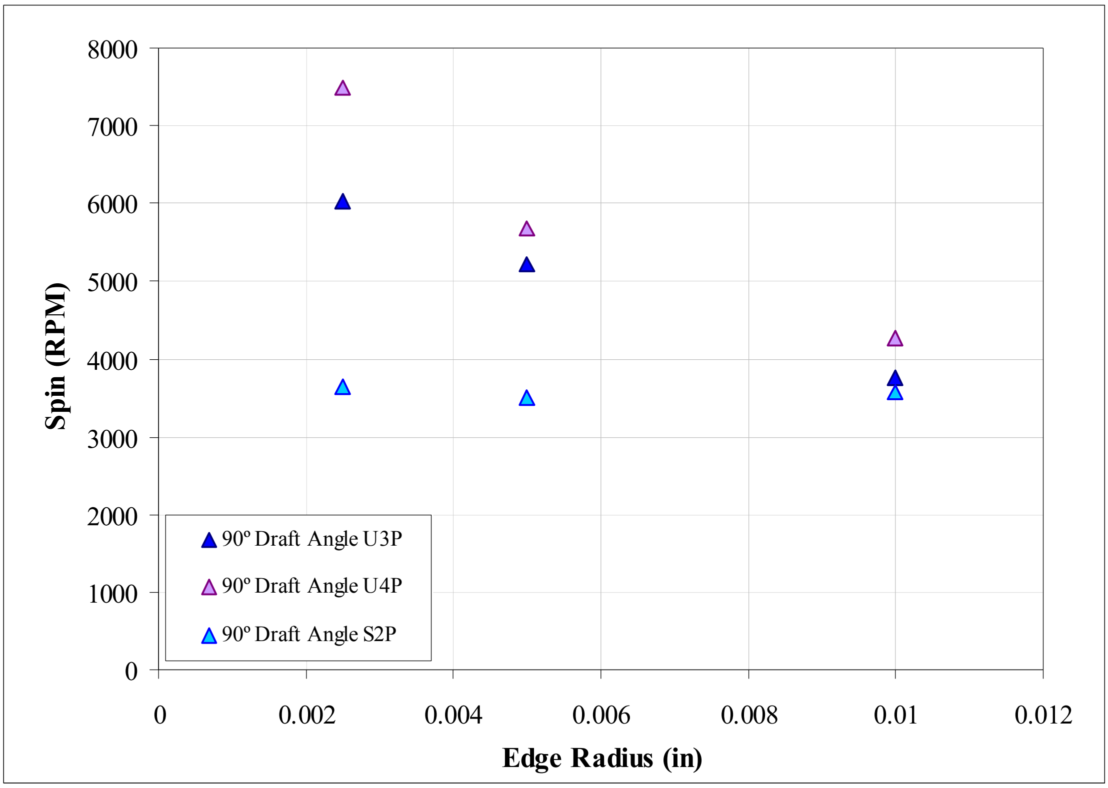


Figure 13: Comparison of edge radius effects for three ball types (U-groove, 35 degree impact)

It can be seen in Figure 13 that, for U-grooves (90 degree draught angle) at an edge radius of 0.010-in, the performance of all three ball types are similar. However, at an edge radius of 0.005-in, the urethane covered balls have clearly superior spin than the Surlyn ball. Finally, at the sharpest edge radius (0.0025-in), the four piece urethane cover ball (U4P) outperforms the three-piece urethane cover ball (U3P). The effect of edge radius at the seventy five degree draught angle is shown in Figure 14. Again, it may be seen that edge radius affects the ball types differently. It has the greatest effect on U4P less effect on U3P and little or no effect on the S2P Surlyn cover ball.

The results shown in Figures 13 and 14 imply that without a control on edge radius, a limitation on any groove profile feature (i.e. depth, width etc.) can be mitigated, at least partially, through ball choice.

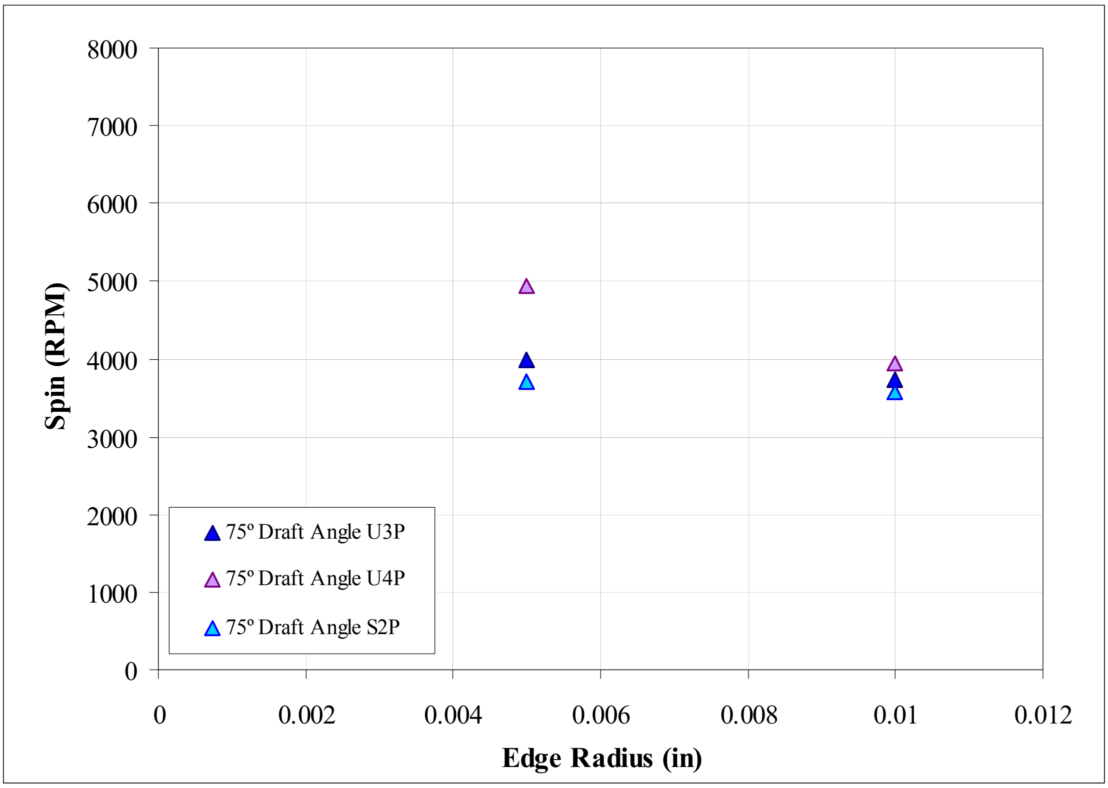


Figure 14: Comparison of edge radius effects for three ball types (75 degree draught angle, 35 degree impact)

As was noted earlier, the effect of edge radius on sixty five and fifty five (V-groove) degree draught angles is negligible as can be seen in Figure 15.

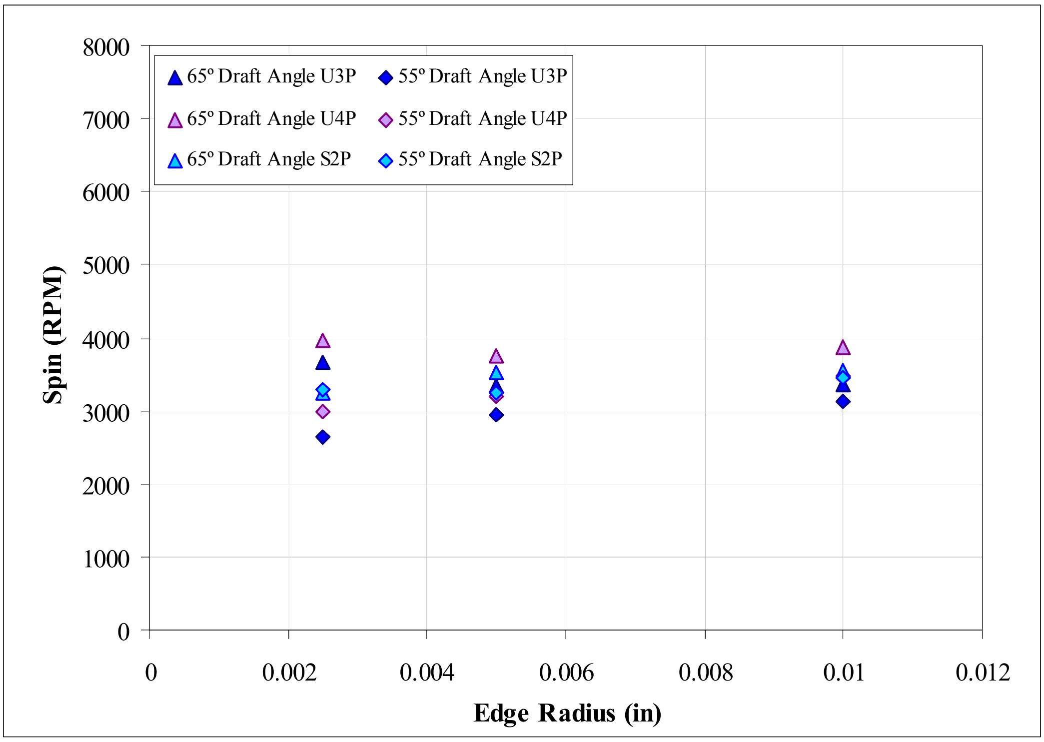


Figure 15: Comparison of edge radius effects for three ball types (65 and 55 degree draught angles, 35 degree impact)

5. Conclusion

It has been shown that the effect of edge radius on spin depends on both the shape of the groove and the ball type. Edge radius is most influential for steep groove sidewalls (ninety and seventy five degrees). It was also shown that the groove shape and edge radius has little effect on the spin of a two piece Surlyn ball. Furthermore, it was shown that the edge radius effects two urethane covered ball types differently.

These findings demonstrate that, in the absence of control on edge radius, regulations limiting the performance of any groove profile feature (i.e. depth, width etc.) can be mitigated, at least partially, by the choice of ball.

6. References

1. **Oblique Impact Testing of Grooved Plates**
   Dec 7, 2006 (see Second Report on Study of Spin Generation, Appendix A)
2. **Procedure to Study the Effect of Groove Specifications on Launch Conditions**
   June 23, 2006 (see Interim Report on Study of Spin Generation, Appendix G, August 7, 2006.)

APPENDIX C

DETERMINATION OF THE AERODYNAMIC BEHAVIOUR OF GOLF BALLS FOR IRON TRAJECTORIES

August 25, 2006

Abstract

The aerodynamic coefficients of lift and drag have been determined for two types of golf ball for a broad range of Reynolds numbers (*Re*) and spin ratios (Θ). This broad range is associated with experimentally determined launch conditions resulting from the impact of golf clubs; 3-iron through sand wedge, in wet and dry conditions, with U- and V- grooved faces.

Introduction

For several years, golf's ruling bodies have relied on the USGA's Indoor Test Range (ITR) [1] for the determination of aerodynamic characteristics used to simulate golf ball trajectories. However, the system in its current form is limited to those launch conditions associated with the driver. This results from physical and accuracy limitations which do not permit measurements within the ITR at low speeds ($Re < 0.7\times10^5$) or high spins ($\Theta > 0.3$ near $Re \approx 1.5\times10^5$).

Several investigators [2] [3] [4] have reported the results of wind tunnel testing at some or all of the regions of interest. These data represent a good illustration of the types of lift and drag behaviour to be expected. However, they do not use aerodynamic dimple geometries of interest, and are expected to be subject to the errors associated with wind tunnel measurements of a side-supported spinning sphere.

Methods

Experimental

Because of the limitations posed by the ITR and the need for better and more applicable data than that available from the literature, it was decided to use the IMAGO golf ball tracking system in order to estimate aerodynamic coefficients in the region of interest. This system allows three-dimensional outdoor trajectories to be recorded with a high degree of accuracy at 50 Hz. The system is subject to environmental conditions, affecting both the ability to track at certain times of the day (for example, when tracking balls directly through the sun), as well as the usefulness of data when turbulence and wind speeds are excessive. To that end, a strict wind speed limit of three mph was imposed for all tests. In addition, testing was performed over the course of several days to ensure that wind and lighting conditions were optimal.

Launch Conditions

In conjunction with an ongoing study of the effects groove geometry on iron performance, modern, three-piece, urethane covered and historical wound, balata covered golf balls were chosen. Table 1 shows the range of launch conditions of interest, extrapolated from the data reported in reference 5.

Table 1: Ball launch conditions derived from reference 5. The current work seeks to provide aerodynamic models that, at a minimum, span the range of spin ratios and Reynolds numbers resulting from these values.

		modern / U-Groove			balata / V-Groove		
Condition	Iron	Speed (ft/s)	Angle (deg)	Spin (rev/s)	Speed (ft/s)	Angle (deg)	Spin (rev/s)
Dry	3i	195	15	85	195	12	97
	5i	189	16	88	188	14	110
	7i	179	18	99	176	17	128
	9i	164	21	119	161	20	146
	SW	131	29	168	129	27	177
Rough	3i	186	14	104	188	13	65
	5i	181	14	108	177	16	59
	7i	170	17	109	162	20	54
	9i	155	22	105	147	25	54
	SW	119	35	88	119	34	64

Given this range of launch conditions, the next step in designing the experiment is to make use of available information in order to gain a first-order estimate of the envelope (the range of Reynolds number and spin ratio) for which aerodynamic data is necessary. To that end, the data of Aoki, et. al. [2], were used to model the trajectories with the launch conditions given in Table 1. The relevant result of this information is the chart of spin ratio versus Reynolds number shown in Figure 1. Whilst these trajectories are by no means assumed to be exact in parameters such as flight time, carry, or landing angle, it is anticipated that the range of spin ratios and Reynolds numbers are reasonable.

To make the most efficient use of the IMAGO tracking system, it was decided that this envelope would be spanned by four trajectories, each given the same initial speed, but at four separate spin rates.

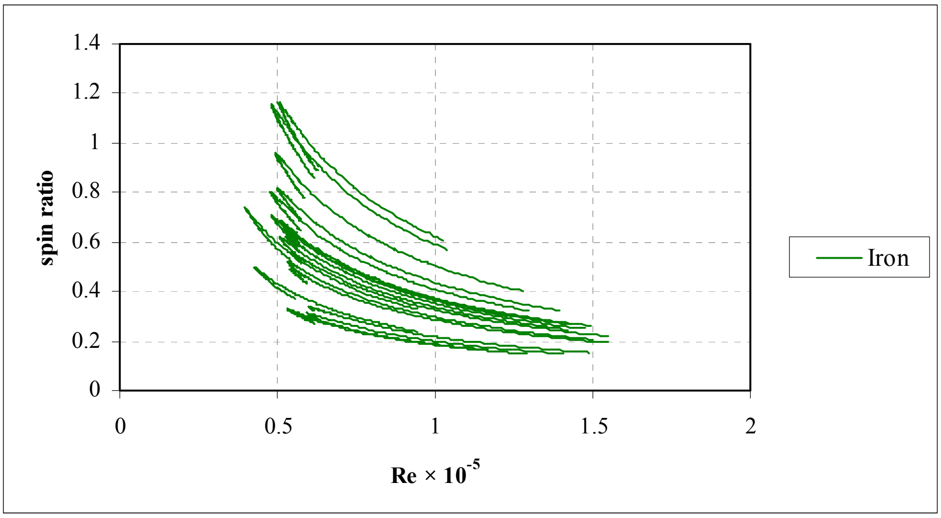


Figure 1: The range of spin ratios and Reynolds numbers anticipated using the launch condition of reference 5 and the aerodynamic data of Aoki et. al. [2]. This will provide the experimental design for the current work.

Given the range of spin ratios and Reynolds numbers shown in Figure 1, it was decided that the most efficient use of apparatus and manpower would be to use a limited set of initial conditions to span the entire envelope. To that end, four spin rates were chosen, along with a fixed initial launch speed (235 ft/s), and the determination that the maximum practical launch angle would be set at all conditions. The spin rates chosen are shown in Table 2. The anticipated Re-SR trajectories are shown in Figure 2.

Table 2: Launch conditions for the outdoor trajectory experiment. The ranges of independent variables expected to be encountered are shown in this column, and correspond to Figure 2.

Condition	Speed	Spin	$Re_{initial}$	$SR_{initial}$	$Re_{min,pred}$	$SR_{max,pred}$
1	235	40	1.9×10^5	0.07	0.62×10^5	0.19
2	235	90	1.9×10^5	0.17	0.49×10^5	0.55
3	235	150	1.9×10^5	0.28	0.47×10^5	1.00
4	235	205	1.9×10^5	0.39	0.53×10^5	1.23

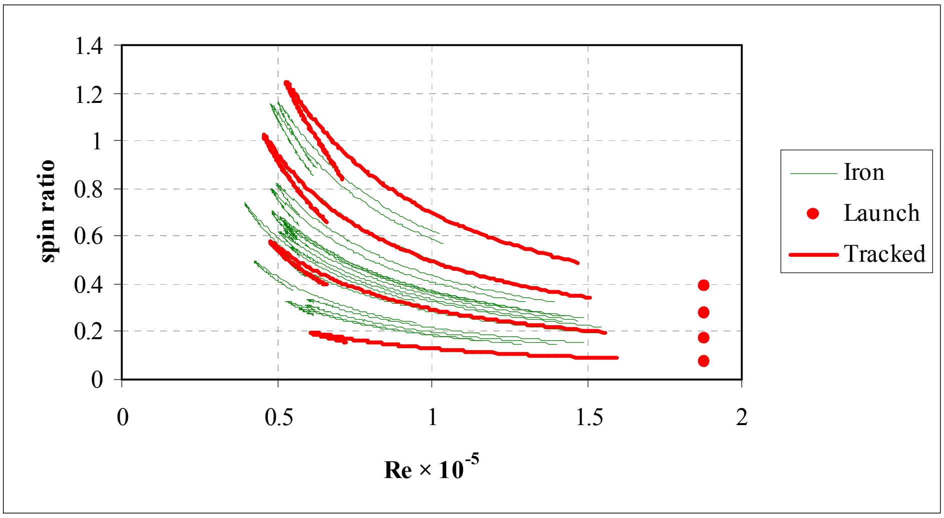


Figure 2: Independent variables Reynolds number and spin ratio, at launch, and anticipated through the tracked trajectories (based on the data of Aoki [2]). The difference in conditions between the launch point and the "tracked" data is due to the acquisition delay, brought about because of the distance between the launcher and the acquisition area outside the building.

The substantial difference between the Reynolds number at launch and those labeled "tracked" exists because of the estimated delay between launch and camera acquisition. This delay occurs principally because the ball launcher is situated approximately 10 yards inside the building. It was for this reason that the launch speeds were chosen.

For each ball type, and at each of the four launcher settings, twenty trajectories were tracked.

Sample Results

Examples of the X- Y- and Z- (corresponding to the longitudinal, vertical, and transverse directions, respectively) coordinate displacements of modern golf balls at each of the four spin rates tested are shown in Figures 3, 4, and 5. It should be noted that these represent raw data obtained from the IMAGO tracking unit, which does not perform any smoothing or interpolation. The trajectories are tracked at 50 Hz, which results in approximately 400 positions per trajectory. The carry distance achieved during these trajectories correlates negatively with the spin rate (Figure 3), though this is not necessarily true of peak trajectory heights (Figure 4).

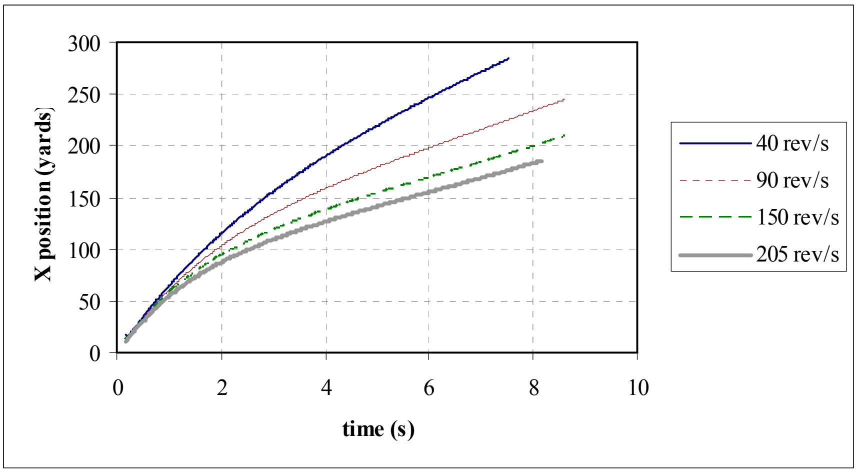


Figure 3: X- position (longitudinally, i.e., down the fairway) of four trajectories as tracked by the IMAGO ball tracking system.

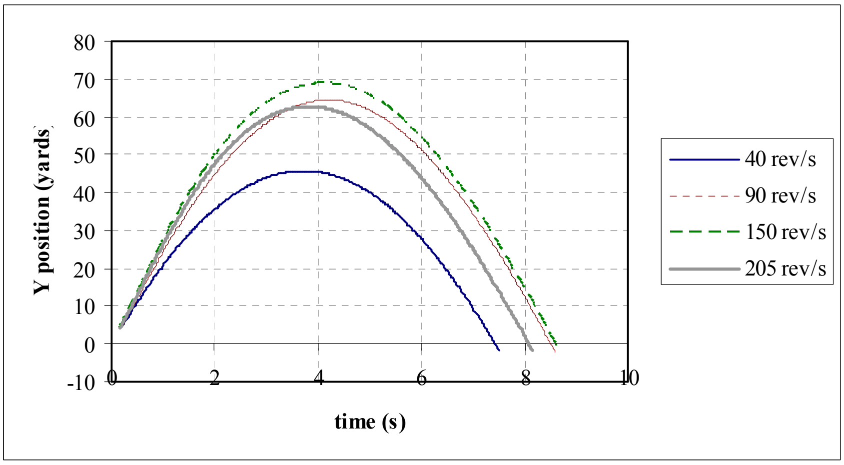


Figure 4: Y- position (vertical) of four trajectories as tracked by the IMAGO ball tracking system.

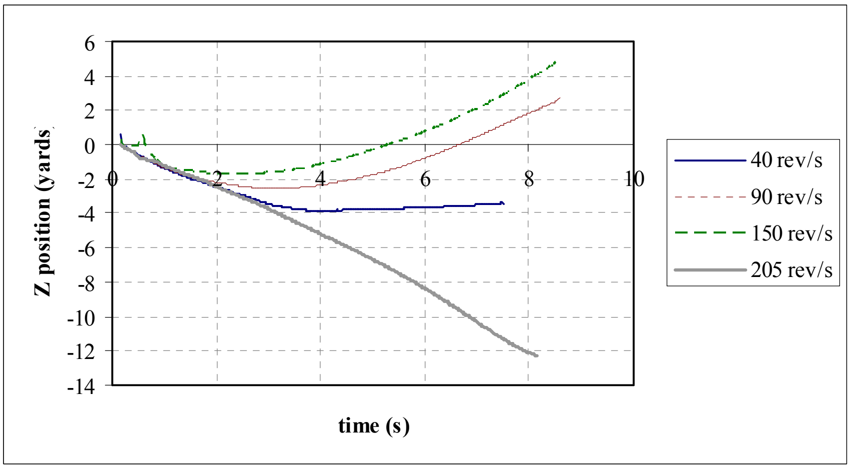


Figure 5: Z- position (transverse) of four trajectories as tracked by the IMAGO ball tracking system.

Analysis

It is the object of this analysis to determine the aerodynamic lift and drag coefficients (C_L and C_D, respectively) from the tracked trajectories. The most direct means of doing this would be to operate on finite differences from the trajectory data directly. However, as smooth as the data appears, there is enough noise that second derivatives become all but useless.

It was therefore resolved to smooth the data in such a way that the derivatives would become useful. The simplest approach was to perform a polynomial interpolation of the spatial variables in time. This would allow the straightforward calculation of derivatives according to the polynomial coefficients. In general, it was found that a sixth-order polynomial was appropriate for the X- and Y- directions, where a third-order polynomial was sufficient for the Z-direction. Using the example of the X-direction position with time, if one fits the data to the polynomial (using least-squares):

$$s_X = \sum_{i=0}^{6} A_i t^i , \tag{1}$$

then one finds that the velocity and acceleration are simply

$$u_X = \sum_{i=1}^{6} i A_i t^{i-1}, \tag{2}$$

$$a_X = \sum_{i=2}^{6} i(i-1) A_i t^{i-2} . \tag{3}$$

The lift and drag coefficients are then determined from

$$\mathbf{a} = \frac{\rho A|\mathbf{u}|}{2m} \begin{bmatrix} -C_D & -C_L\cos(\gamma) & -C_L\sin(\gamma) \\ C_L\cos(\gamma) & -C_D & 0 \\ -C_L\sin(\gamma) & 0 & -C_D \end{bmatrix} \mathbf{u} - \mathbf{g}, \tag{4}$$

where γ is the spin axis inclination in the Y-Z plane, ρ is the air density, A is the ball cross-sectional area, m is the ball mass, and $\mathbf{g}$ is the gravity vector. This results in three equations for three unknowns (C_L, C_D, and γ). The evaluation of aerodynamic coefficients may thus be determined at arbitrarily chosen points along the trajectory.

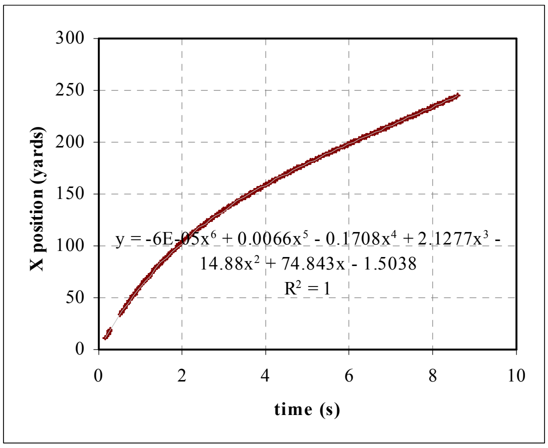
As the IMAGO system does not track spin (indeed, there are no systems available to date that have been able to measure spin during the entire trajectory), it is necessary to model spin decay in order to associate an appropriate spin ratio with the aerodynamic coefficients. To do this, we make use of the scalar equation

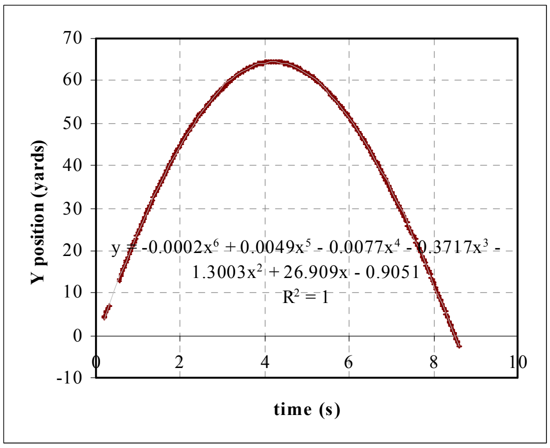
$$\dot{\omega} = -C_{\omega} \frac{\omega|\mathbf{u}|}{r}. \qquad (5)$$

This equation can be solved explicitly, recognising that the integral of $|\mathbf{u}|$ equals the path length s. Thus,

$$\omega = \omega_0 \exp\left(\frac{-C_{\omega} s}{r}\right). \qquad (6)$$

The simplicity of this scheme is beneficial in that it is computationally inexpensive. Several trajectories can be evaluated completely in the time it takes to perform an ITR-like analysis of a single trajectory.





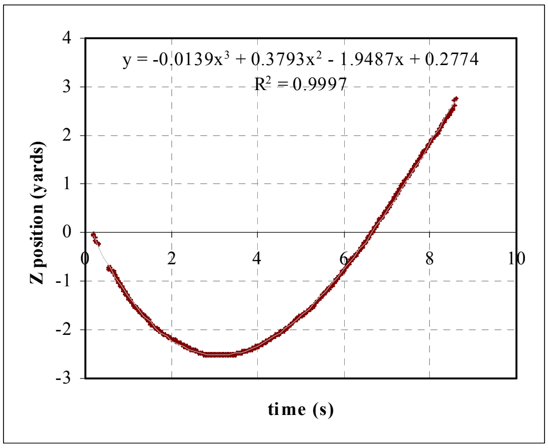


Figure 6: Polynomial fits of trajectory data presented in Figures 3-5. The R^2 value in all cases is above 0.99. From top left, clockwise: X- (direction of fairway), Y- (vertical), and Z-(transverse) position.

Results

Experimental Envelope: Independent Variables

The ranges of spin ratios and Reynolds numbers derived from these trajectories were far greater than those hoped for based on the data of Aoki (see Figure 7). This occurs because of higher than anticipated trajectories and longer flight times. In particular, the low Reynolds numbers achieved expands the range of the USGA's data (the lowest Re tested on the ITR is approximately 0.7×10^5). The spin decay used in this derivation was based on a C_ω of 2×10^{-5}, consistent with the value used in the Overall Distance Standard. This value will be verified in the next section.

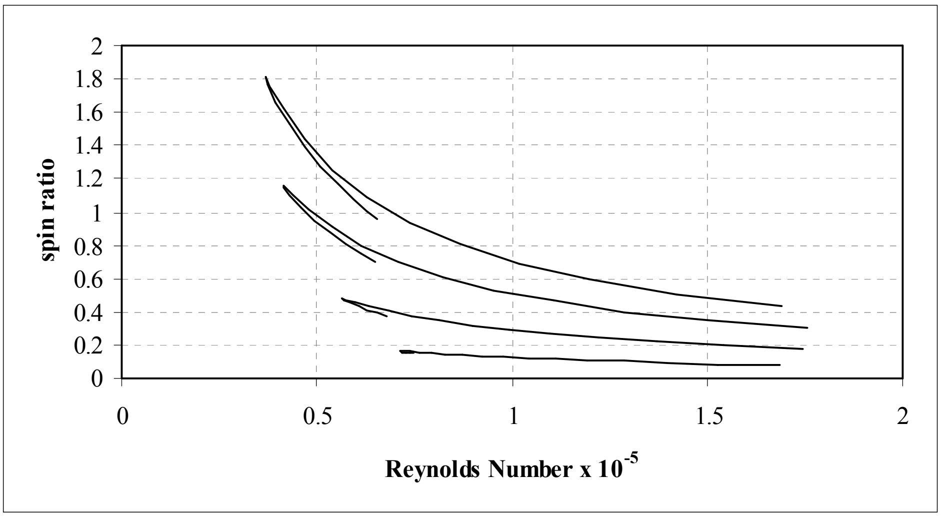


Figure 7: Range of independent variables for which lift and drag properties were found during the experiment and analysis using outdoor trajectories. The total range of values is much greater than anticipated based on the initial data of Aoki [2]. This appears to indicate that drag coefficients are somewhat lower than the initial prediction.

Dependent Variables: Lift and Drag

Figures 8 and 9 show the aerodynamic behaviour of the modern tour ball and the balata ball, respectively. Immediately obvious is that spin ratio is the stronger of the two dimensionless parameters in determining aerodynamic coefficients over a broad range of conditions. Indeed, the Reynolds number dependence that is so important in detailed modelling of driver trajectories is of diminished consequence at elevated spin ratios. This is consistent with the findings of Bearman and Harvey [3], Smits and Smith [4], and others. However, the Reynolds number dependence (in particular, of C_L) is pronounced in the case of the modern tour ball, as seen in Figure 8 at low spin ratios.

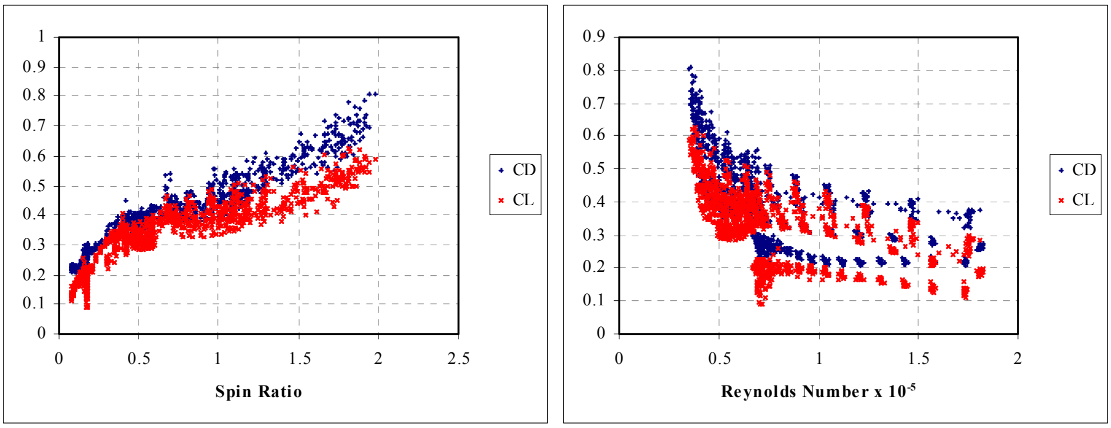


Figure 8: Lift and drag coefficients of the modern tour ball plotted against spin ratio (left), and Reynolds number (right).

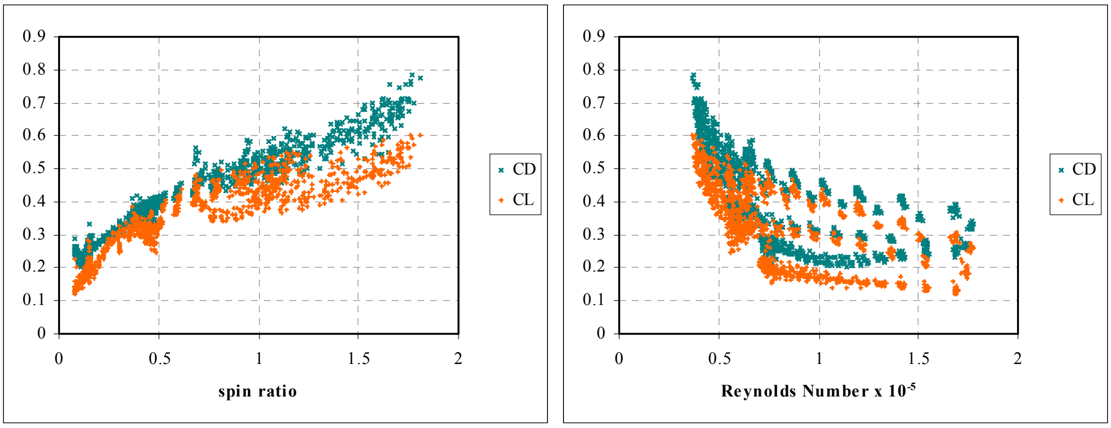


Figure 9: Lift and drag coefficients of the balata ball, plotted against spin ratio (left), and Reynolds number (right).

In order to simulate the full range of iron launch conditions, the following interpolary fits were used. These were determined using the commercially available program "TableCurve3D", and fits were selected based on F-statistic from among equations linear in the dependent variable. The one exception was C_L in the case of the modern, where a slightly more complex curve was selected to account for the Reynolds number dependence at low Θ and *Re*. For the modern tour ball, then:

$$C_L = 0.4221 - 0.1208 \cdot (\ln(\mathrm{Re}))^2 + 0.03225 \cdot \Theta^{2.5} + 0.1134 \cdot \ln(\Theta), \quad (7)$$

$$C_D = 0.06639 - 0.6312 \cdot \Theta \ln(\Theta) + 0.3963 \cdot \Theta^2, \quad (8)$$

and for the balata ball:

$$C_L = 0.3996 + 0.1583 \cdot \ln(\Theta) + 0.03790 \cdot \Theta^{-0.5}, \qquad (9)$$

$$C_D = 0.1403 - 0.3406 \cdot \Theta \ln(\Theta) + 0.3747 \cdot \Theta^{1.5}. \qquad (10)$$

Fits of the lift coefficients had values of R^2 above 0.92, and the corresponding values R^2 for the drag coefficients were above 0.94.

Verification

An experiment was conducted in order to evaluate the landing angle, spin, and carry of the modern tour ball when struck under the following situations: by a five-iron with wet (i.e., using a wetted paper interface) and dry conditions, and by a sand wedge in wet and dry conditions. Both clubs were Cleveland blanks with V-groove inserts. Details of this experiment, which used the pneumatic mechanical golfer, along with a fixed-mount high-speed video camera to record inbound conditions, will be described in a later report.

Equations (7) and (8) were used, along with the launch conditions measured during the experiment, to simulate the trajectories of all four conditions. The results are shown in Table 3.

Table 3: Simulated and measured terminal landing conditions for modern tour ball golf balls hit under different launch conditions. Simulations and experiments took place at 79-81 deg. F., 29.9 in Hg., and 80% relative humidity. The lift and drag correlations used in simulation are given in Equations (7) and (8).

Launch Conditions					Simulation			Measurement		
Club	Interface	Speed (ft/s)	Angle (deg)	Spin (rev/s)	Carry (y)	Angle (deg)	Spin (rev/s)	Carry (y)	Angle (deg)	Spin (rev/s)
5i	Dry	189.5	16.6	91.1	188.4	45.2	76.6	187.6	46.6	76.0
5i	Wet	189.1	19.5	54.6	204.4	43.6	45.3	204.3	41.8	43.2
SW	Dry	130.1	25.7	178.8	108.9	48.3	161.1	110.7	48.0	154.3
SW	Wet	126.7	37	47	115.9	51.9	41.8	115.6	50.5	38.0

Overall agreement is excellent, with an average carry error of -0.2 yards, angle error of 0.5 deg., and terminal spin error of 3.3 rev/s. This low spin error demonstrates the appropriate choice of the spin decay constant C_ω consistent with the Overall Distance Standard.

Predictions

This experiment was conducted in support of iron spin research, as described earlier. The landing conditions associated with the launch conditions found in reference 5 are given in Table 4. All simulations were conducted under USGA Overall Distance Standard environmental conditions (namely, 75° F, 30 in. Hg., 50% relative humidity, zero wind speed).

In general, differences between the modern/U-groove (modern/U) specification and the balata/V-groove (balata/V) specification are greatly exaggerated in the wet "rough" condition. For example, the approach angle difference between the two combinations in the sand wedge configuration is about one degree in the dry, compared with three degrees in the wet. At the other end of the spectrum, the landing angle difference goes from about four degrees to eight. Differences in spin on approach correlate roughly to the differences in launch spin in Table 1. Approach speeds for the balata/V combinations are notably greater from the rough than the dry, the reverse of the case with the modern/U combinations, principally due to the greatly diminished spin-induced drag (for example, using to Equation (10) and the data from Table 1, it can be shown that the initial drag for balata/V 7i-dry is nearly 30% greater than the 7i-rough).

Table 4: Ball approach conditions at the end of flight under different launch conditions. Launch conditions corresponding to these results are given in Table 1.

		modern / U-groove			balata / V-groove		
Condition	Iron	Speed (ft/s)	Angle (deg)	Spin (rev/s)	Speed (ft/s)	Angle (deg)	Spin (rev/s)
Dry	3i	83	44	71	80	40	82
	5i	82	44	74	78	43	93
	7i	81	46	84	76	46	110
	9i	78	48	103	74	48	128
	SW	72	51	151	68	50	160
Rough	3i	79	43	89	85	35	55
	5i	78	42	93	85	36	50
	7i	78	44	94	85	39	47
	9i	78	46	92	83	43	47
	SW	75	52	80	76	49	58

Conclusions

A method of determining aerodynamic lift and drag coefficients using outdoor testing and trajectory measurement has been demonstrated. Ranges of the independent variables Reynolds number and spin ratio, far greater than achievable using the ITR, have been tested. It has been found that using this data in simulations of modern tour ball iron trajectories results in successful prediction of carry distance and landing conditions. Finally, predictions have been provided showing the difference in terminal conditions for modern tour ball combined with U-groove irons and balata covered ball combined with V-groove irons.

References

1. Quintavalla, S.J. (2000) The Indoor Test Range (ITR) Technical Description and Operation Manual (United States Golf Association)
2. Aoki, K., et. al. (1998), "Flow Characteristics of a Golf Ball Using Visualization Techniques", *Science and Golf II*, Human Kinetics.
3. P.W. Bearman, J.K. Harvey (1976) Golf Ball Aerodynamics, *Aeronautical Quarterly,* pp. 112 - 122
4. Smits, A.J., Spina, E.F., Smith, D.R. (1990) "Measurements of Lift, Drag, and Spin Rate Decay", USGA Aero Report #9
5. Tour Player Testing of Pre-1990 and Modern Club/Ball Combinations", (see Interim Report on Study of Spin Generation, Appendix A, August 7, 2006.)

APPENDIX D

RESULTS OF EXPERIMENT ON GOLF BALL IMPACT WITH GREEN SURFACE

October 30, 2006

1. PURPOSE

The USGA is in the process of studying the effect of groove technology on the game. It has been demonstrated how the groove profile affects the ball launch[1]. Another study has demonstrated the aerodynamic trajectory of shots using U and V grooves from the fairway and rough[2].

The purpose of this study is to determine how the ball will bounce and roll on a surface representative of a championship quality green as a function of the ball's spin and trajectory immediately prior to impact.

2. BACKGROUND

Player launch data was collected using U groove irons with three-piece, urethane covered balls (U3P) and V groove irons with wound, balata covered balls from both fairway and rough lies[3]. Launch conditions for a range of irons (from 3 iron to sand wedge) were interpolated/extrapolated from this data. Launch conditions for these irons are summarised in Table 1.

The aerodynamic model developed for iron trajectories[2] was used to generate the pre-impact conditions (speed, angle and spin) using the launch conditions in Table 1. The resulting impact conditions are listed in Table 2.

A series of nineteen test settings were designed to efficiently envelope the landing conditions provided in Table 2. Figure 1 plots the landing conditions and the test settings.

Table 1: Launch Conditions

Club	Groove/Ball	Launch Conditions (Fairway) Speed (ft/s)	Launch Conditions (Fairway) Angle (deg)	Launch Conditions (Fairway) Spin (RPM)	Launch Conditions (Rough) Speed (ft/s)	Launch Conditions (Rough) Angle (deg)	Launch Conditions (Rough) Spin (RPM)
3	U/modern	195	15	5100	186	13	6200
5	U/modern	189	16	5300	181	14	6500
7	U/modern	179	18	5900	170	17	6600
9	U/modern	164	21	7100	155	22	6300
SW	U/modern	131	29	10100	119	35	5300
3	V/balata	195	12	5800	188	13	3900
5	V/balata	188	14	6600	177	16	3500
7	V/balata	176	17	7700	162	20	3300
9	V/balata	161	20	8800	147	25	3300
SW	V/balata	129	27	10600	119	34	3800

Table 2: Landing Conditions

Club	Groove/Ball	Landing Conditions (Fairway) Speed (ft/s)	Landing Conditions (Fairway) Angle (deg)	Landing Conditions (Fairway) Spin (RPM)	Landing Conditions (Rough) Speed (ft/s)	Landing Conditions (Rough) Angle (deg)	Landing Conditions (Rough) Spin (RPM)
3	U/modern	83	44	4300	79	43	5300
5	U/modern	82	44	4400	78	42	5600
7	U/modern	81	46	5100	78	44	5600
9	U/modern	78	48	6200	78	46	5500
SW	U/modern	72	51	9100	75	52	4800
3	V/balata	80	40	4900	85	35	3300
5	V/balata	78	43	5600	85	36	3000
7	V/balata	76	46	6600	85	39	2800
9	V/balata	74	48	7700	83	43	2800
SW	V/balata	68	50	9600	76	49	3500

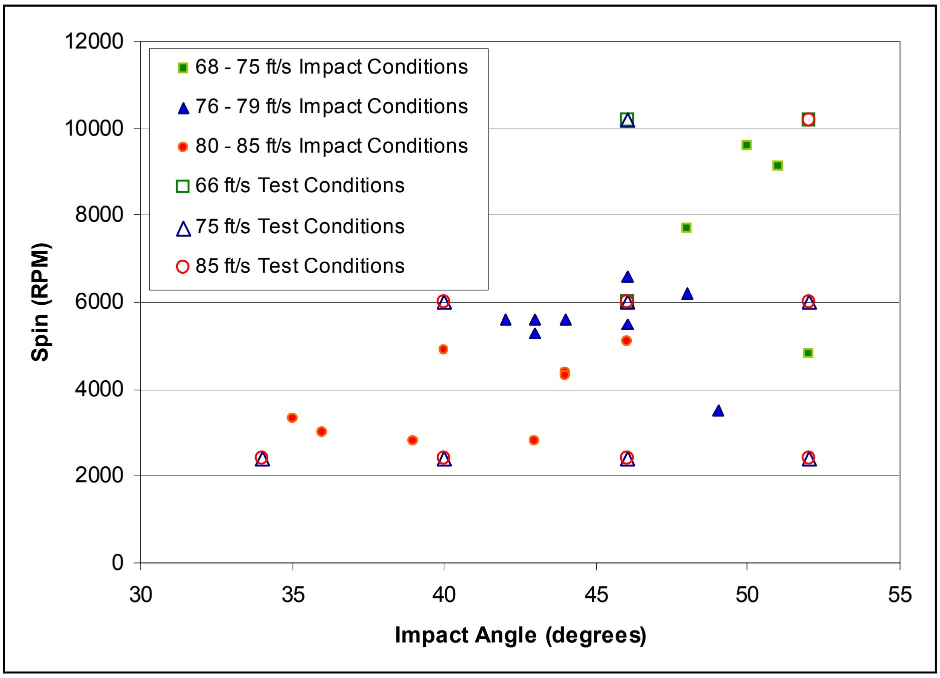


Figure 1: Impact conditions and test settings

3. PROCEDURE

A greens turf nursery at Trump National Golf Club (Bedminster, NJ, USA) was used for the testing. The nursery was constructed to USGA greens specifications and is generally maintained in the same manner as the greens on the course. Irrigation was restricted on the nursery leading up to the test so that the firmness could be increased to championship conditions. On the morning of the test, the greens were double cut and rolled to a Stimpmeter reading of between 10 and 11 feet. The available turf on the nursery measured approximately 40' by 100'.

A modified pitching machine was used to launch the ball with the desired test settings (as shown in Figure 1). High speed video was used to capture the actual impact and hence the inbound and outbound ball speed, angle and spin were measured. The distance of the first bounce was recorded along with the total distance the ball bounced and rolled.
The nineteen settings were launched within the same general area (approximately 3' x 3'). The equipment was then moved and the nineteen settings were repeated. This was then done again

such that each setting was tested three times for a total of 57 impacts. Figure 2 shows a photograph of the test setup.

Figure 2: Test apparatus

4. RESULTS

4.1. Post Impact Conditions

The ball conditions (speed, angle and spin) after the first impact were measured by the high speed camera. Each of these three variables was compared to the three inbound conditions. It was found that the outbound ball speed and angle were mainly a function of the inbound angle. The outbound spin rate was mainly influenced by the inbound spin rate. These results are plotted in Figures 3, 4 and 5.

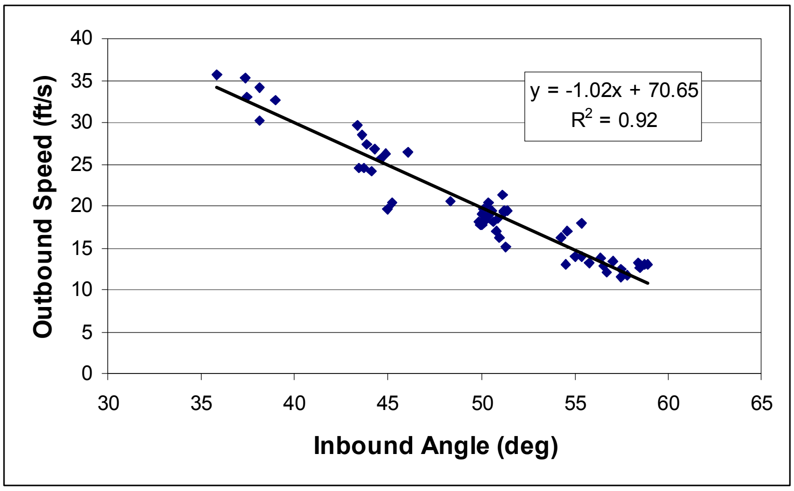


Figure 3: Rebound ball speed

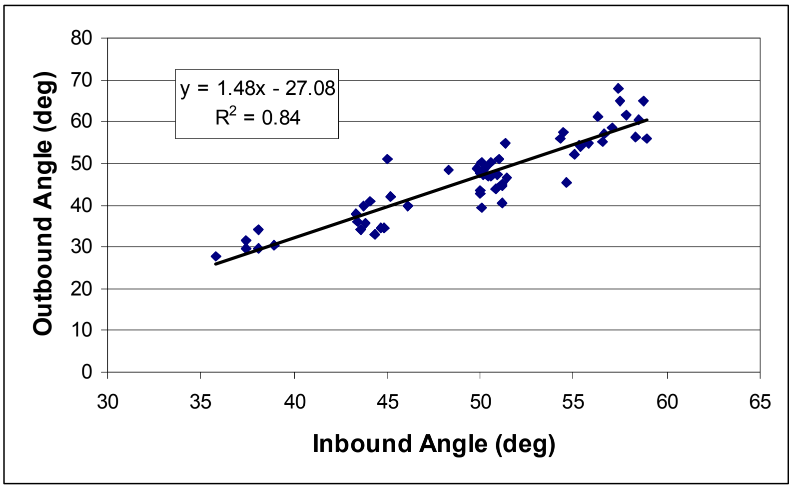


Figure 4: Rebound angle

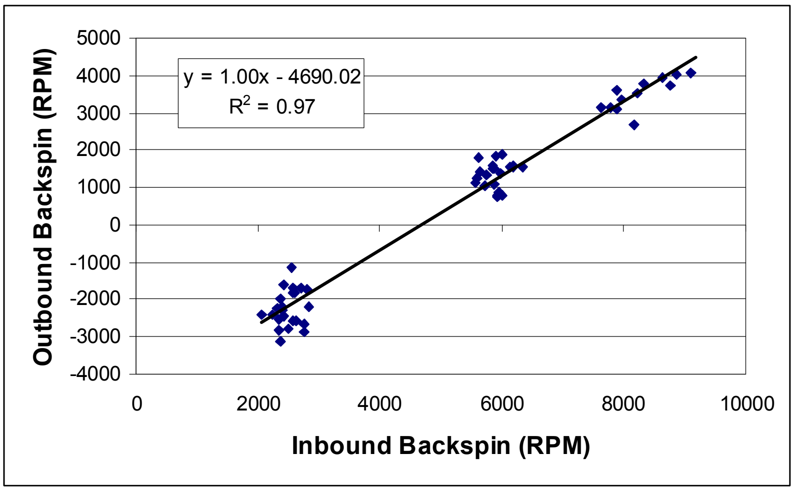


Figure 5: Rebound spin rate

4.2. First Bounce

Since the inbound angle largely determines the rebound speed and rebound angle, it is not surprising that the first bounce distance can be accurately estimated using only the inbound angle (R^2=91.0%). The addition of inbound speed to the correlation does not contribute significantly to an improved estimate (R^2=92.5%). The linear regression of the first bounce distance (feet) as a function of the inbound angle (degrees) yields:

$$Bounce_{1st} = 72.3 - 1.2\theta_{in} \tag{4.1}$$

The estimated first bounce is plotted against the measured first bounce in Figure 6.

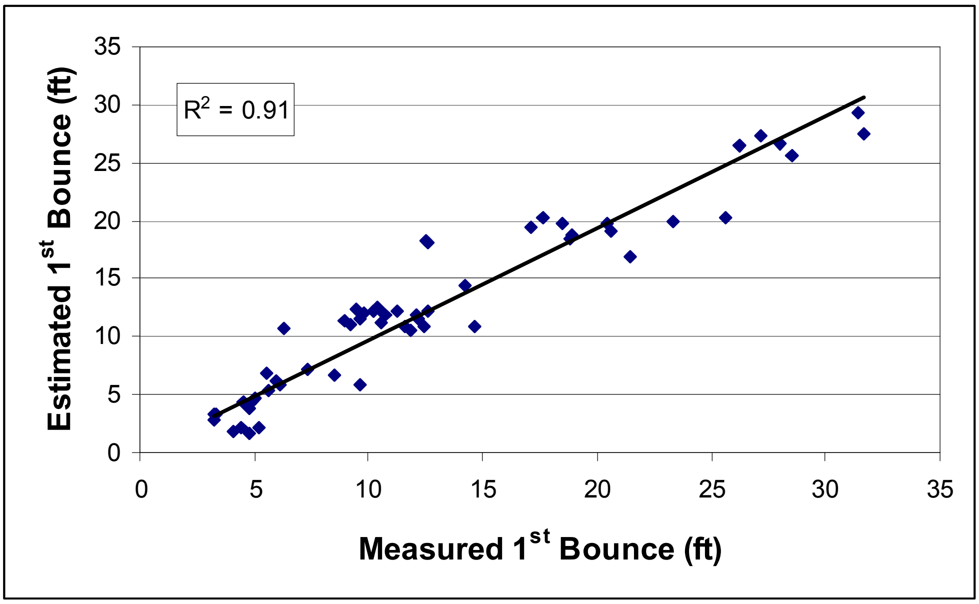


Figure 6: First bounce

4.3. Total Bounce and Roll

The bounce and roll of the ball after the first bounce depends, approximately equally on the rebound speed angle and spin rate (R^2≈60% for all three variables). Therefore, based on the results of Section 4.1, it is unsurprising that the total bounce and roll is strongly a function of the inbound angle (R^2=74%) and the inbound spin (R^2=55%). The linear regression equation of the total bounce and roll (in feet) as a function of inbound angle (degrees) and spin (RPM) is:

$$Total = 246 - 3.54\theta_{in} - 0.0065\omega_{in} \tag{4.2}$$

The estimated total bounce and roll is plotted against the measured values in Figure 7.

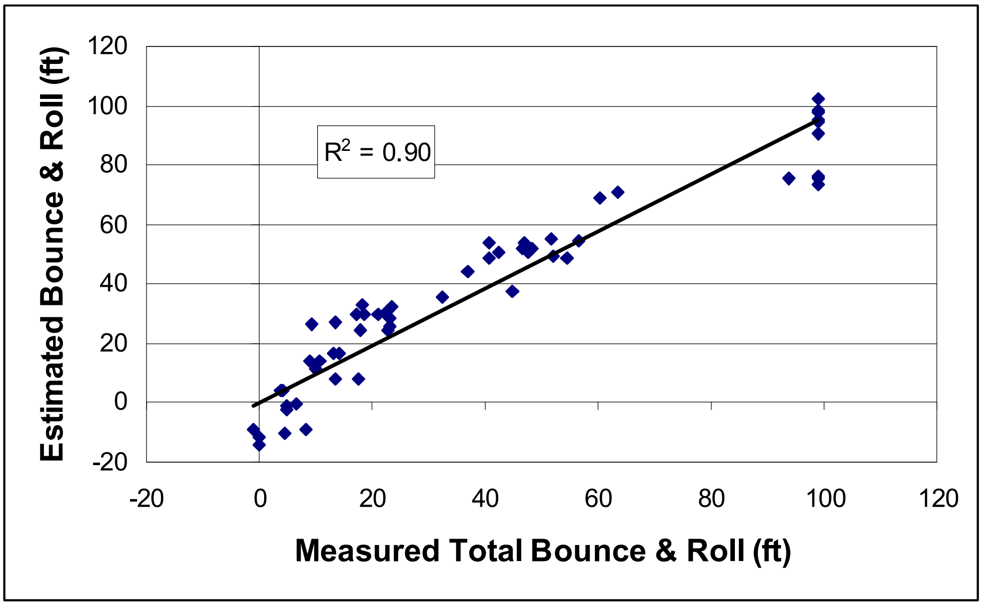


Figure 7: Total bounce and roll

5. Predictions of Behaviour from Fairway and Rough

The correlations identified in Section 4.3 were then used to determine differences in bounce and roll performance using the actual launch conditions measured from the player testing[1] for the 5, 8 and SW for the U-groove/modern ball and V-groove/balata combinations from the fairway and the rough (listed in Table 3). Again, using the aerodynamic simulation[2], the landing conditions were predicted. These are listed in Table 4.

The resulting total bounce and roll for the two groove/ball configurations is plotted in Figure 8. Also shown in Figure 8 is the estimated bounce and roll for the modern ball from the fairway. It should be noted that these estimates are for a flat green. Typically, however there would be a general pitch from back to front such that these estimates of bounce and roll would be reduced. However, the observations of the effect of grooves would be similar. These are:

1) For all clubs, the total bounce and roll of the V-groove/balata combination from the rough is approximately 60% higher than the U-groove/modern combination.

2) For the 5 and 8 irons, the U-groove/modern bounce and roll from the rough is nearly identical to that from the fairway.

Table 3: Measured Launch Conditions

Club	Groove/Ball	Launch Conditions (Fairway)			Launch Conditions (Rough)		
		Speed (ft/s)	Angle (deg)	Spin (RPM)	Speed (ft/s)	Angle (deg)	Spin (RPM)
5	U/modern	189	16	5300	181	14	6500
8	U/modern	172	19	6500	163	19	6500
SW	U/modern	131	29	10100	119	35	5300
5	V/balata	188	14	6600	177	16	3500
8	V/balata	169	18	8200	155	23	3200
SW	V/balata	129	27	10600	119	34	3800

Table 4: Landing Conditions from Measured Launch

Club	Groove/Ball	Landing Conditions (Fairway)			Landing Conditions (Rough)		
		Speed (ft/s)	Angle (deg)	Spin (RPM)	Speed (ft/s)	Angle (deg)	Spin (RPM)
5	U/modern	82	44	4500	78	42	5600
8	U/modern	79	47	5600	78	45	5600
SW	U/modern	72	51	9100	75	51	4800
5	V/balata	78	43	5600	85	36	3000
8	V/balata	75	47	7100	84	41	2800
SW	V/balata	68	50	9600	76	49	3500

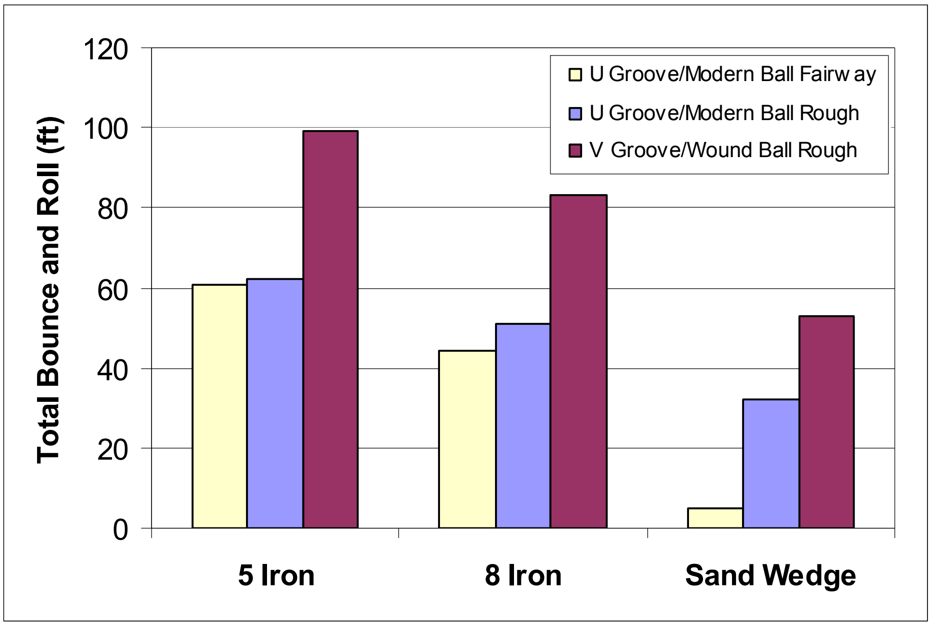


Figure 8: Effect of groove and lie on total bounce and roll

6. Conclusions

It has been shown that the total bounce and roll after a shot hits the green is primarily a function of the inbound angle and secondarily to the inbound spin. The landing conditions for shots from the rough with the V-groove/balata have significantly shallower inbound angle and lower spin rates than the U-groove/modern ball combination. Therefore, as expected, the total bounce and roll with the V-groove is significantly higher than the U-groove.

7. References

1) R&A/USGA, ***Interim Report on Study of Spin Generation***, August 7, 2006
2) R&A/USGA, ***Determination of the Aerodynamic Behaviour of Golf Balls for Iron Trajectories***, Aug 2006 (see Second Report on Study of Spin Generation, Appendix C)
3) R&A/USGA, ***Tour Player Testing of Pre-1990 and Modern Club/Ball Combinations***, June 2006 (see Interim Report on Study of Spin Generation, Appendix A)

APPENDIX E

TOUR PLAYER TESTING OF
V-LIKE GROOVED IRON CLUBS

November 29, 2006

INTRODUCTION

Earlier tests demonstrated that the configuration of modern club faces with U-grooves have significant performance improvements over the traditional V-groove in grassy lies. Building on the results of this player testing, an extensive set of test plates was designed and fabricated. Each of these plates was tested in the laboratory at a variety of angles using grass surrogate materials to determine their effectiveness at creating spin. From the laboratory testing, a set of modified face treatment specifications was developed for non V-shaped groove profiles that would produce spin performance similar to that of a traditional V-groove in grassy lies. The objective of this subsequent player testing was to verify the effects of equipment manufactured to modified face treatment specifications when used by golf tour professionals in shots from light rough.

The testing was conducted in two phases. The first used a large selection of clubs; some with U-grooves, some with V-grooves and some designed with groove profiles that were not V-shaped yet performed like V-grooves. These clubs were tested by players from a professional golf developmental tour. The second phase used a smaller subset of modified clubs and PGA Tour players for the testing. In both phases the launch conditions, measured by a radar tracking unit, were obtained from fairway lies and in the light rough.

TEST EQUIPMENT

Several sets of equipment were used in the player testing. Each set contained a 5 iron, an 8 iron and a sand wedge. The clubs used in all of the sets were forged muscle-back irons. These clubs were obtained from the manufacturer without grooves in the face. The faces were pocketed using a CNC mill to accept machined face inserts with the desired groove configurations and surface roughness. All sets were matched for length, lie and swingweight.

The groove configurations used in the test clubs were selected based on their performance in laboratory testing. With the exception of sets that were U-grooves and V-grooves at current conformance limits, all of the groove configurations chosen exhibited V-like groove performance in the laboratory testing with a grass surrogate.[1] Figure 1 shows the groove profiles for which club sets were manufactured. The dimensions of these grooves are listed in Table 1.

Figure 1 –Groove Profiles for Player Test Clubs

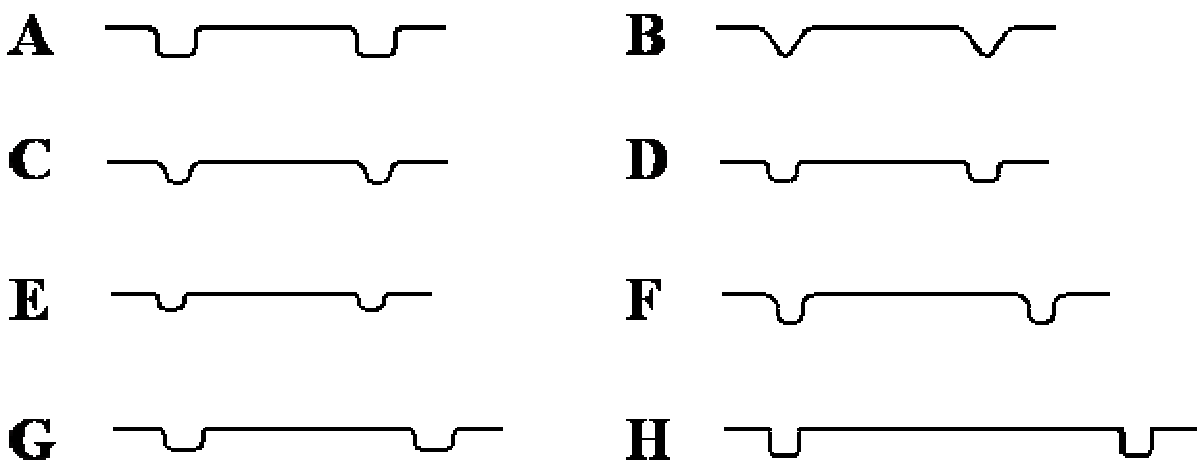


Table 1 – Test Club Groove Specifications

Set ID	Groove ID	Edge Radius (in)	Groove Spacing* (in)	Groove Width** (in)	Groove Depth (in)
A	U	0.005	0.14	0.03	0.02
B	V	0.005	0.14	0.03	0.02
C	WD101	0.01	0.14	0.0225	0.015
D	RWD101	0.005	0.14	0.023	0.014
E	RWD102	0.0025	0.14	0.02	0.01
F	WS101	0.01	0.175	0.0225	0.02
G	VRS123	0.005	0.175	0.03	0.0148
H	VRS101	0.0025	0.245	0.0219	0.02

* Groove Spacing is centreline to centreline
** Groove Width using 45° method

DEVELOPMENTAL TOUR PLAYER TESTING METHODOLOGY

The first phase of the player testing was performed by six professional golfers currently competing on a developmental tour. Each player was asked to hit shots using each loft of the U-groove and V-groove sets from light rough (they were also asked to hit the U-groove clubs from a fairway lie where there is no grass/debris between the clubface and ball, hereafter referred to as the dry condition.) They were then asked to hit shots using each loft of two of the sets of V-like groove sets (sets C through F in Table 1) from light rough. Using this approach each of the V-like groove sets, C through F, were tested by four players. (Time constraints prohibited complete testing of club sets G and H. However the limited test results for these sets are included in the data.)

For each shot radar was used to track the launch and the resulting trajectory and high speed video, using either a manual or automated trigger, was used to capture the incoming club trajectory and the initial ball launch. The testing was conducted so as to randomise as much as possible the test variables whilst maintaining test efficiency.

DEVELOPMENTAL TOUR PLAYER TEST RESULTS

The venue used in this phase of the testing used different agronomic procedures (e.g. growth regulators and overseeding) than the venue used in the earlier player testing conducted in the spring.[2] Despite this the measured launch conditions were relatively consistent across the six players and since each player hit different club sets the results of the groove configurations were grouped for clarity and consistency, Figure 2.

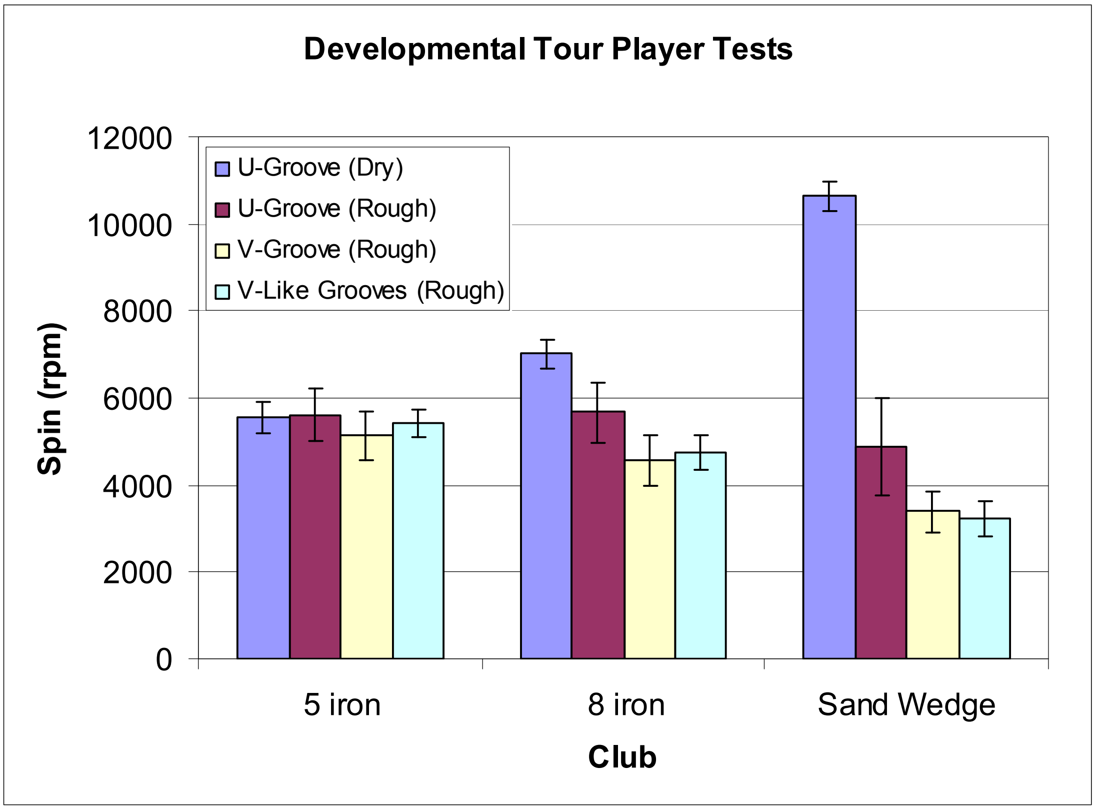


Figure 2 –Developmental Tour Player Test Results

From the data it can be observed that for both the 8 iron and the SW the V-like groove clubs performed very similarly to the V-groove and different from the U-groove. Data for the 5 iron showed less discernable differences between the various groove configurations. The overall trends in the results were also consistent with the lab tests[1] and the previous player tests[2]: the dry spin increasing from the 5 iron through the sand wedge; the U-groove showing similar spins from the rough at both the 5 iron and 8 iron lofts and a decreased spin rate with the sand wedge; and the V-groove (and V-like grooves) exhibiting less spin than the U-groove at all lofts.

PGA TOUR PLAYER TESTING METHODOLOGY

The second phase of the player testing was performed by nine professional golfers from the PGA Tour. Three players were tested at the 2006 Chrysler Classic of Greensboro Open in Greensboro, NC, USA. Six additional players were tested at the 2006 Funai Classic at Walt Disney World Resort. For the PGA Tour player testing the number of V-like groove configurations was pared down to only the C and F configurations listed in Table 1.

At the Chrysler Classic each player was asked to hit shots using two of the lofts of U-groove and V-groove sets from light rough (they were also asked to hit the U-groove clubs from a dry lie.) They were then asked to hit shots using the same two lofts of the two selected V-like groove sets (sets C and F in Table 1) from light rough. Since this proved to be somewhat time consuming, the sequence of testing was changed at the Funai Classic. At the Funai Classic each player was asked to hit shots using only a single loft of U-groove and V-groove sets from light rough (they were also asked to hit the U-groove clubs from a dry lie.) They were then asked to hit shots using the same loft of the two selected V-like groove sets (sets C and F in Table 1) from light rough. Using this approach each loft of each groove configuration was tested by four players.

Once again, for each shot radar was used to track the launch and the resulting trajectory and high speed video was used to capture the incoming club trajectory and the initial ball launch. The testing was again randomised as much as practical.

PGA TOUR PLAYER TEST RESULTS

Like the developmental tour player testing, the results of the groove configurations were grouped for clarity and consistency. The results for the nine PGA Tour players are shown in Figure 3.

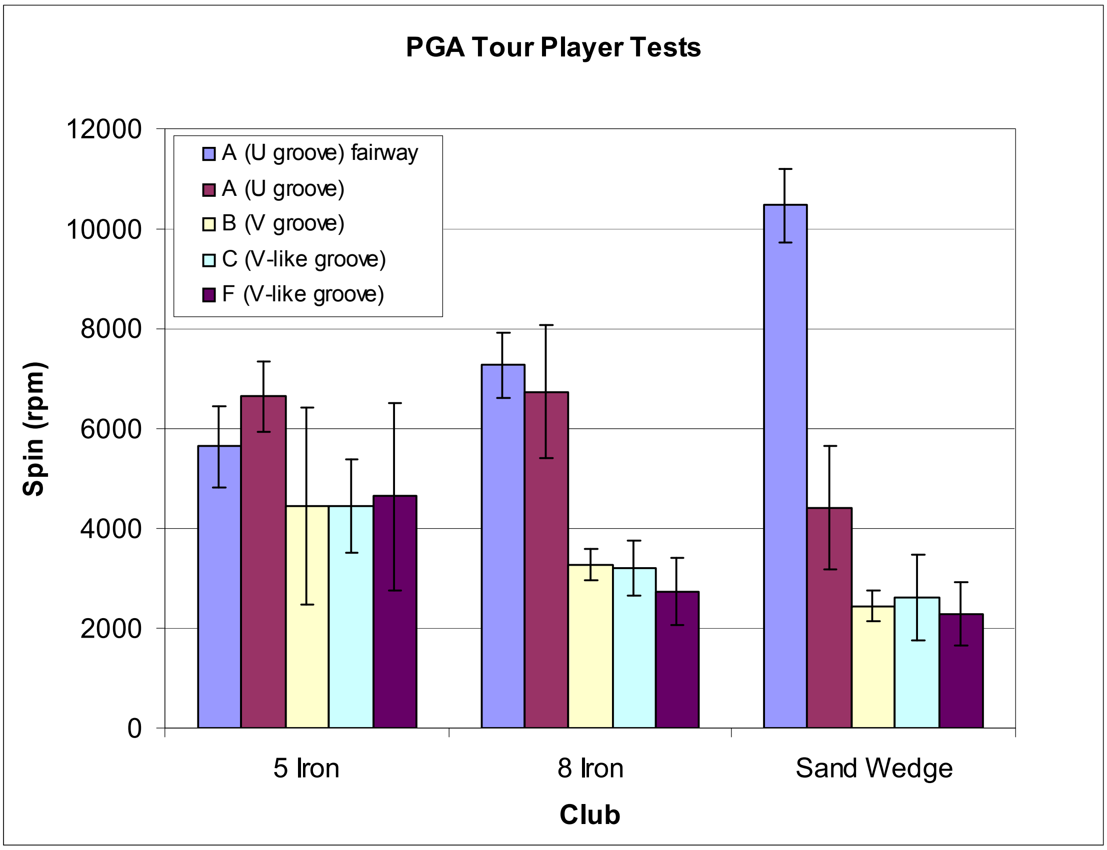


Figure 3 – Developmental tour I: PGA Tour Player Test Results

From the data it can be observed that for all lofts the V-like groove clubs performed very similarly to the V-grooves and different from the U-grooves. And, as was the case in the developmental tour testing, the data from the PGA Tour player testing were also consistent with lab tests[1] and the previous player tests[2].

The confidence intervals of the data (as a percentage of the mean spin) for the U-groove, V-groove and V-like groove configurations in the rough are similar; approximately +/- 22% on average, which is about double the confidence interval for the dry configuration. This indicates that shot variability between the different groove configurations is comparable.

SUMMARY AND CONCLUSIONS

Player testing was performed with professional golfers currently competing on a developmental tour and the PGA Tour. The objective of this testing was to verify the effects of equipment manufactured to modified face treatment specifications when used by golf tour professionals in shots from light rough.

The results of the player tests showed that equipment could be manufactured with modified face treatment specifications to perform like traditional V-groove clubs when used by golf tour professionals in lies in the light rough.

REFERENCES

1. OBLIQUE IMPACT TESTING OF GROOVED PLATES…,
   December 7, 2006 (see Second Report on Study of Spin Generation, Appendix A)

2. TOUR PLAYER TESTING OF PRE-1990 AND MODERN CLUB/BALL COMBINATIONS,
   June 5, 2006 (see Interim Report on Study of Spin Generation, Appendix A)

APPENDIX F

MEASUREMENT OF AMATEUR PLAYER SHOT DISPERSION

November 29, 2006

SUMMARY

Measurement of amateur golfer shot dispersion was conducted over two days at the Walt Disney World Resort's Palm and Eagle Pines golf courses. The objective of this data gathering was to quantify the percentage of shots that amateur golfers are able to hit, from various distances and lie conditions, which stay on the green. 824 data points from 412 shots were taken, 412 data points representing the locations of the approach shot and 412 data points representing the final position of the ball in the area of the target green. The dispersion data for shots from the rough were of primary interest. All of the measured shots occurred during normal stipulated rounds of golf.

TEST CONDITIONS

The data was collected using laser range finders from Laser Atlanta. The laser range finders, when initially zeroed on the test hole location, provide data that allows for measurement of the distance from the hole as well as the x and y position of each shot for precise mapping of dispersion. The holes selected for the observation and measurement were chosen to be relatively flat, straight holes without tree obstructions in the rough and without forced carries over water hazards on the approach to the green. The holes selected were all par four that ranged in length from 340 yards to 385 yards, from the most commonly played tee markers. This range of length holes was selected to such that approach shots with a variety of lengths between 100 and 175 yards would likely be observed.

The three holes used in the study were; the 385 yard, Hole 5 on the Disney Palm Course, host of the PGA Tour Funai Classic, and the 367 yard, Hole 1 and 351 yard, Hole 2 on Disney's Eagle Pines Course, designed by Pete Dye. The fairway widths ranged from 28 to 38 yards wide at a distance of 100 to 175 yards out from the hole. The rough was a 1.0 – 1.75 inch high

Bermudagrass. The approximate area of the three greens was 750 square yards on Hole 5 of the Palm course, 440 square yards for Hole 1 of the Eagle Pines course, and 375 square yards for Hole 2 of the Eagle Pines course. (An average green has an area of about 550 to 600 square yards.)

AMATEUR PLAYER RESULTS

Table 1 is a summary of the dispersion data collected for the three holes used in this study. Of the 412 approach shots measured, 217 were measured from the rough. The percentage of shots that finished on the green when hit from the rough varied for each hole and was dependent on range from hole as well the gross area of the green. The two holes on the Eagle Pines course had roughly half the area of the one green on the Palm course, this was likely a contributing factor to a substantial difference in the percentage of shots from the rough finishing on the green, 4-5% vs. 21%. This large difference between the percentages of shots finishing on the green was less pronounced for the shots hit from the fairway for the two courses, 10-21% vs. 25%. Overall 13.1% of the approach shots measured finished on the green.

Figures 1 through 3 are scatter plots of all of the shots measured for the three holes. Each red point represents the starting location of a single approach shot, whilst there is a corresponding single yellow point representing the final location of that approach shot. These scatter plots have been superimposed over an artist's rendition of the hole. The data was mapped to the artist's rendition using land marks on the hole including the 100, 150, and 200 yard marks, as well as the outline of the green and edges of the fairway (black points). Red, white and blue concentric circles were also overlaid on the image to indicate 100, 150, and 200 yard radii from the centre of the green.

Table 1 Summary of amateur dispersion data collected for the 824 measured shots.

	Lie	**Hole 1**	**Hole 2**	**Hole 5**	**Overall**
Approach	Fairway	43	51	74	168
Location	Rough	50	54	113	217
	Bunker	4	13	9	26
Percentage	Fairway	21%	10%	25%	19.4%
On Green	Rough	4%	5%	21%	13.1 %
	Bunker	0%	7%	0%	3.8%
Green Area		440 sq. yds.	375 sq. yds.	750 sq. yds.	

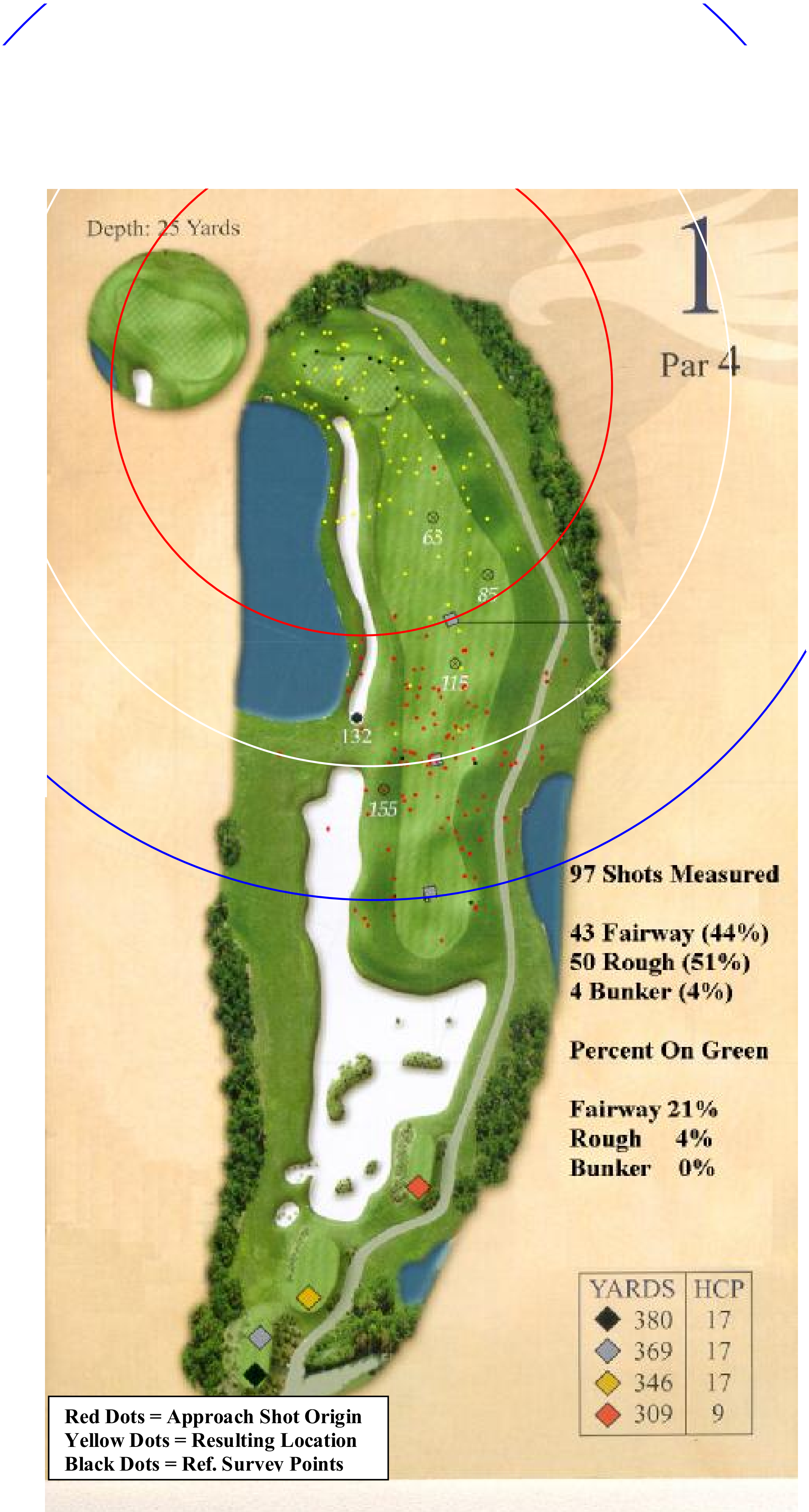


Figure 1 Eagle Pines Hole 1 Shot Distribution.

Figure 2 Eagle Pines Hole 2 Shot Distribution.

Figure 3 Palm Course Hole 5 shot distribution.

In order to analyse the data in a more cohesive manner, the three data sets were combined by superimposing the centres of the greens at the origin and rotating each set of data such that 150 yard markers were all in alignment. With this combined set of data further analysis can be made regarding accuracy from the rough and fairway which can be quantified in terms of radial distance from the hole as opposed to the binary information of being on or off of the green. Figures 4 and 5 are histograms displaying the percentages of approach shots that finish within 5 yard ranges or concentric rings from the hole. For example, referring to Figure 4, for shots from both the fairway and rough, approximately 14% finish between 20 and 25 yards from the hole. Superimposed on the histogram in red is a curve representing the cumulative percentage of shots with in a given radial distance from the hole. Both Figures 4 and 5 indicate that approximately 95% of all of the approach shots from the fairway and rough finish within 100 yards of the hole. The 50% cut off does, however, vary for the two lies. 50% of all of the approach shots from the rough finish within 30 yards of the hole, where from the fairway, nearly 60% of the shots are within 30 yards of the hole. In order to see the actual percentage of shots that were on the green, the bars of the histogram were coloured green.

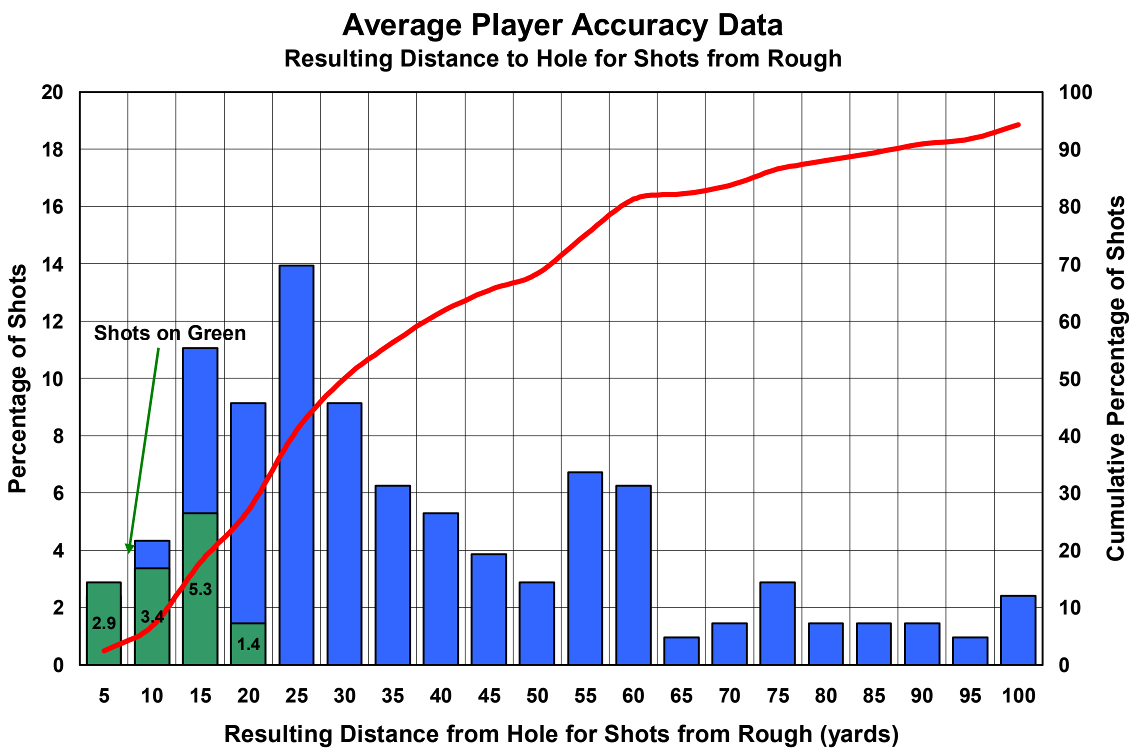


Figure 4 Amateur player accuracy data for shots from the rough.

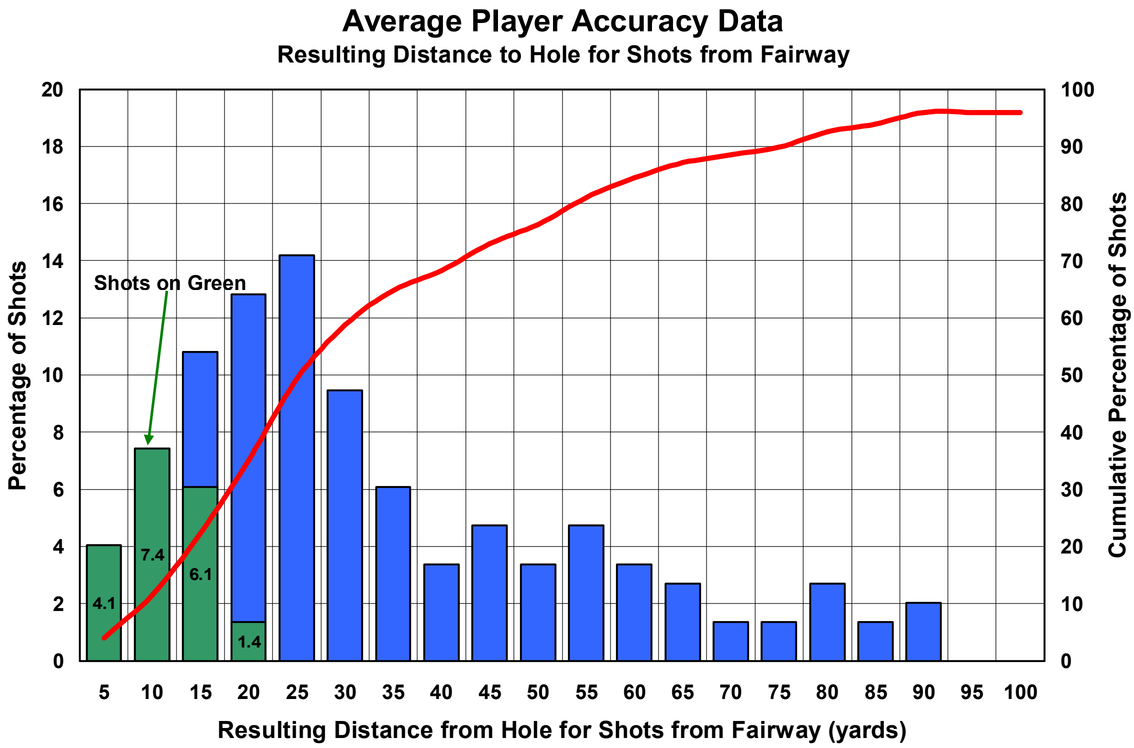


Figure 5 Amateur player accuracy data for shots from the fairway.

Figure 6 is a plot of the distance to the hole after the approach shot as a function of the approach shot distance for both fairway and rough lies. The data was partitioned into 25 yard bins and the mean value and 95% confidence interval for that partition were calculated. There is the expected trend in the data that demonstrates that the longer the approach shot, the further away from the hole the approach shot will finish. In addition, Figure 6 also illustrates that, on average, shots from the rough finish further away from the hole than shots from the fairway within 175 yards. What may not have been expected, beyond 175 yards the mean of the shots from the rough were actually closer than the mean of the shots from the fairway. It is important to note, however, that the mean values for both shots from the rough and from the fairway are within the opposing data set's 95% confidence intervals.

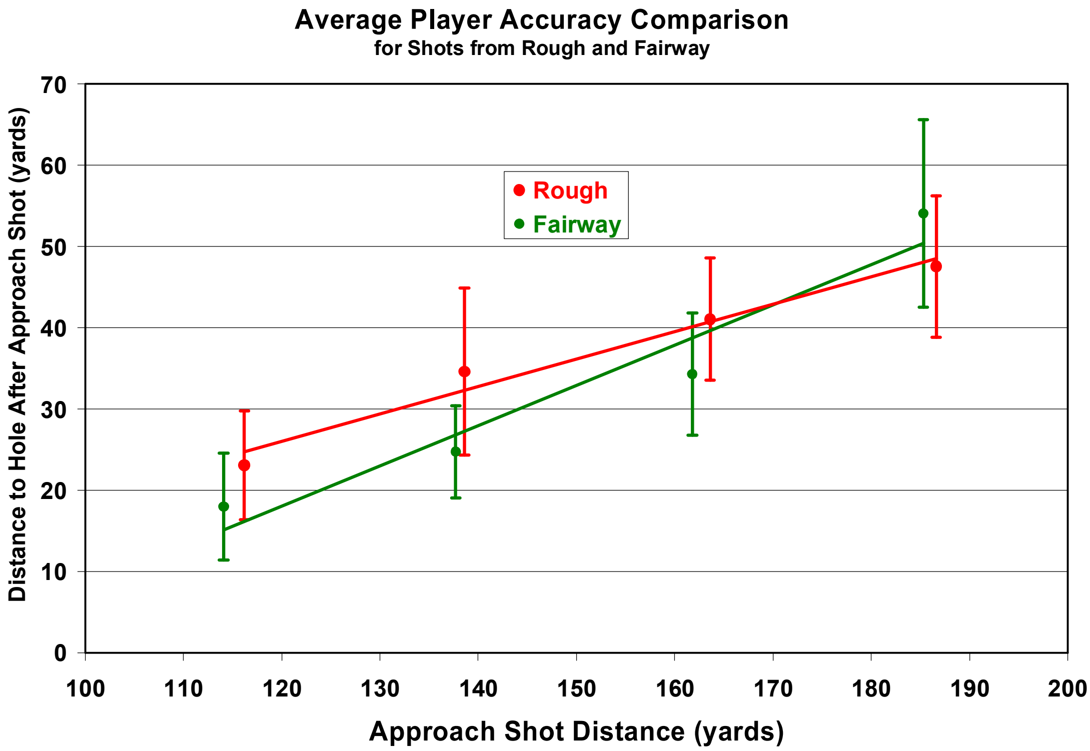


Figure 6 Distance to Hole versus Approach Shot Distance

CONCLUSIONS

The primary goal of this data collection study was to determine an approximate percentage of shots that amateur players hit from the rough that finish on the green. The results show that 13.1 percent of the time this population of amateur players successfully kept the ball on the green for shots from the rough. This 13.1 percent represents data from a full range of approach shots from within 100 yards out to just beyond 200 yards, as well as a range in the size of the target green. As expected, this set of data indicates that the longer the approach shot, the farther away from the hole the approach shot will finish on average. In addition, the smaller the area of the green, the fewer the percentage of shots on average that finish on the green.

APPENDIX G

MEASUREMENT OF AMATEUR PLAYER SPIN DATA FROM THE ROUGH

December 4, 2006

INTRODUCTION

Measurement of amateur golfer launch condition data out of the rough with irons was conducted at the United States Golf Association's test range (additional testing has been conducted by The R&A which corroborates the findings presented herein). Fifteen different amateur golfers participated in this research study. The golfers involved in the testing had GHIN handicap indexes that were uniformly distributed over a range from 1.9 to 19.8. The Trackman RADAR system was used to capture the launch condition data. The main objectives of this research were to determine the spin rates and variability associated with amateur players shots out of the rough. Of particular interest were the effects on spin due to groove geometry and ball cover material.

TEST CONDITIONS

The testing was divided into two portions, one evaluating the effect of groove geometry on spin, and the second evaluating the effect of the ball cover material on spin. Two sets of irons were used in the testing; one U-groove design representing the limit of conformance, and the other representing a full dimension V-groove. The two balls used in the testing were a Surlyn covered, two piece "distance" ball (S2P) and a modern, three-piece urethane covered ball (U3P). The Trackman RADAR was set up 15 feet directly behind the test subject's ball at address to capture spin, launch angle, velocity, and landing dispersion information. A target for the player was provided and was located approximately 175 yards away from the test subjects. The subjects were instructed to simply use the target as a directional marker and that they should not alter their swings to reach the target. A 15 foot by 15 foot test area of rough was prepared for the testing. The rye grass was mowed to an approximate 1 inch mower height and was cross cut and raked to remove obvious dead thatch and loose grass clippings. The choice of rough height was selected such that the ball when hand placed would have approximately one half of the ball diameter exposed. The rough test area was carefully cut in ¼ inch increments down to this 1 inch height until the ball could be hand placed in a repeatable fashion to the desired lie.

TEST RESULTS

The first round of testing was conducted with 11 players, four irons, and the modern, three-piece urethane covered ball. The irons used in this test were 8 irons with a U-groove and a V-groove, and 5 irons with a U-groove and V-groove. Each player went through a random cycle of these four clubs two times, each time hitting 5 shots, for a total of 40 shots. Figure 1 is a bar chart of the results of this test for the 5 iron U and V grooved clubs. For 10 of the 11 subjects, the mean spin value for U-groove 5 iron had more spin than the V-groove 5 iron. Six of the subjects, primarily subjects with the lowest handicaps, had a statistically significant difference between the spin of the U and V grooved clubs.

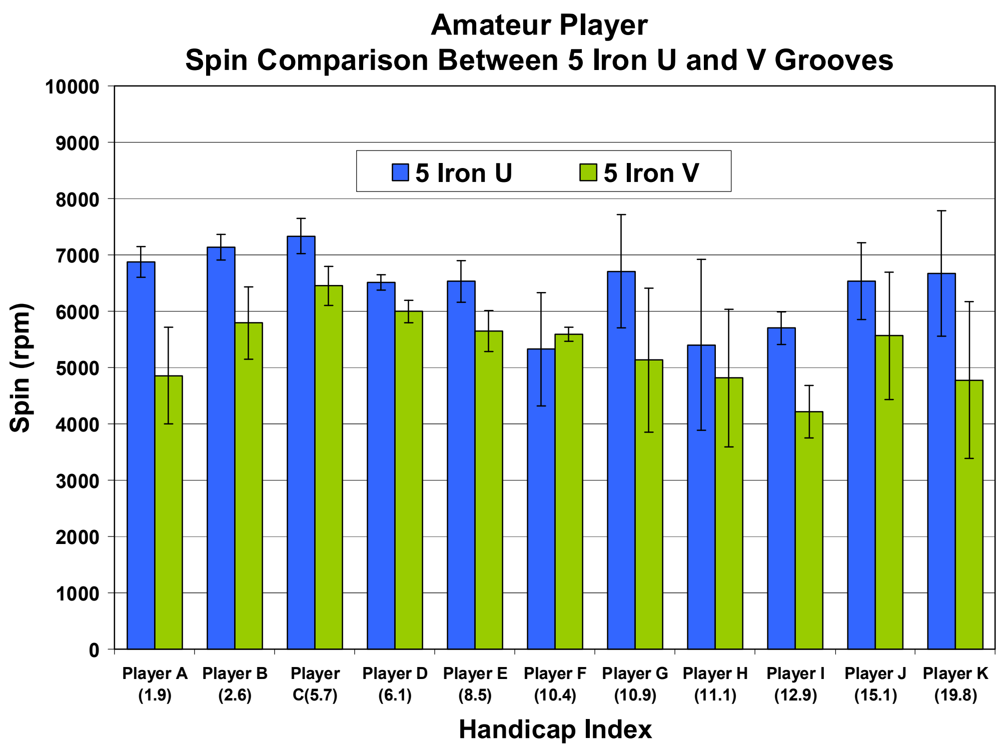


Figure 1 Comparison of Amateur Player Launch Spin for 5 Iron U and V Grooved Clubs.

Figure 2 is a bar chart of the results of this test for the 8 iron U and V grooved irons. All eleven subjects had a mean spin value for U-groove 8 iron that was higher than that of the V-groove 8 iron. Ten of the eleven subjects had statistically significant differences in spin between the U- and the V-grooved 8 irons. An additional observation from this testing is that there is a slight correlation (R^2= 0.3) between handicap and confidence interval or standard deviation in the data. Not surprisingly, it was observed that there was a tendency for the lower handicap subjects to have smaller standard deviations in their data.

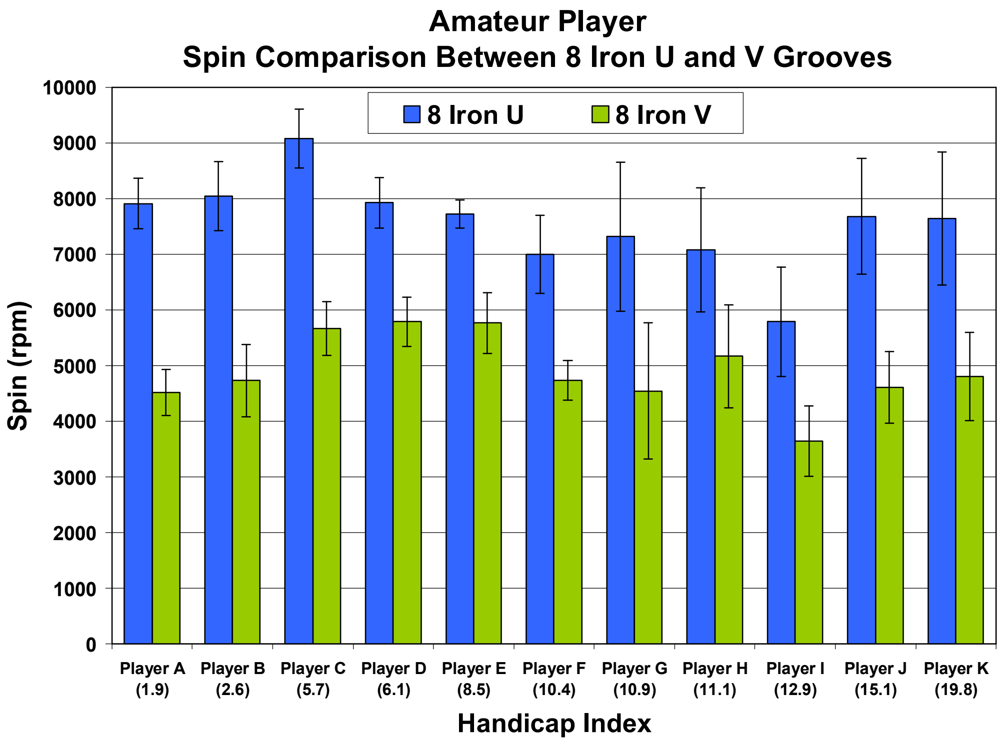


Figure 2 Comparison of Amateur Player Launch Spin for 8 Iron U and V Grooved Clubs.

Figure 3 is a bar chart of the player averages for both the 5 and 8, U- and V-grooved clubs. When the data is combined for all players there is a statistically significant difference in the means for the spin values for the U- and V-grooved clubs for both the 5 and 8 irons. At both lofts the U-groove had higher spin than the V-groove.

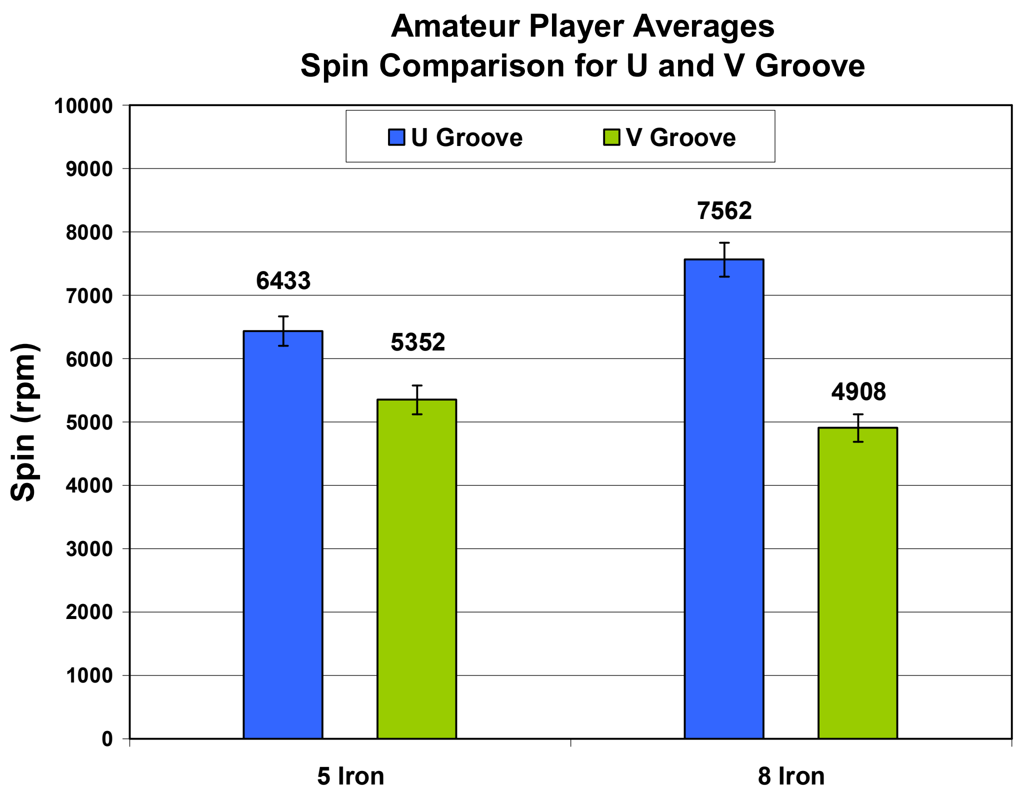


Figure 3 Comparisons of Player Average Launch Spins.

The second segment of the testing involved six subjects using only the 8 iron U- and V-grooved clubs with two ball constructions. The testing was conducted in a similar manner such that the four test combinations were randomly ordered and conducted in two cycles of five shots per test. The intention of these tests was to see if spin values that were dependent on groove construction with urethane covered balls exhibited the same behaviour with Surlyn covered balls. Each subject hit both urethane and Surlyn to ensure that the groove dependency with urethane that was seen with previous tests, was still exhibited by the subjects in these tests. Figure 4 is a bar chart of the 6 subjects spin results for the four combinations tested. Each player in this series of tests again had higher mean spin values for the U-groove over the V-groove with urethane covered balls, and each showed a statistically significant difference between the U-groove and V-groove. For the tests including the Surlyn covered balls, however, there was not the distinct difference between the U- and V-grooved clubs. Although most of the subjects did demonstrate a slight decrease in spin from the U-groove to the V-groove, only one subject showed a statistically significant difference between the U- and V-grooves, and none of the differences were nearly as large a drop in spin as was seen with the urethane covered balls. In fact, the spin rates of both the U and V groove tests with Surlyn were not statistically different than the spin values obtained with the V-groove urethane combination. Figure 5 is a plot of the average of all subject's values for the Surlyn and urethane comparison. Again, there is a clear distinction in spin values for the U-groove and the V-groove with urethane covered balls and very little difference with Surlyn covered balls.

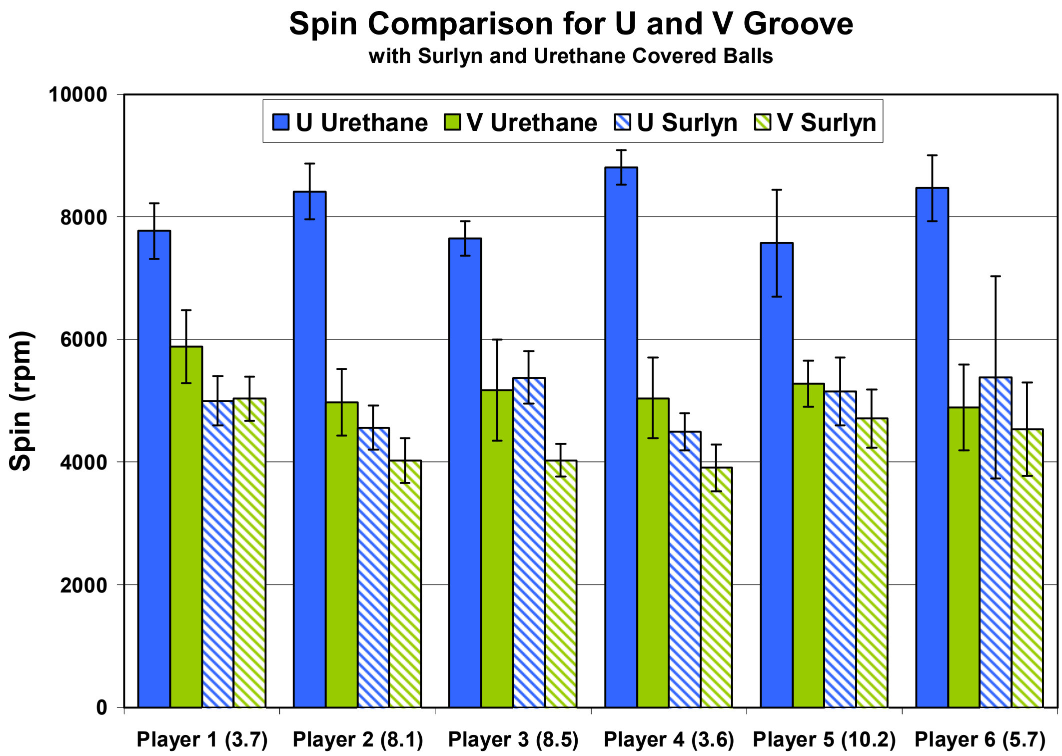


Figure 4 Spin comparison for amateur spin values with urethane and Surlyn covered balls.

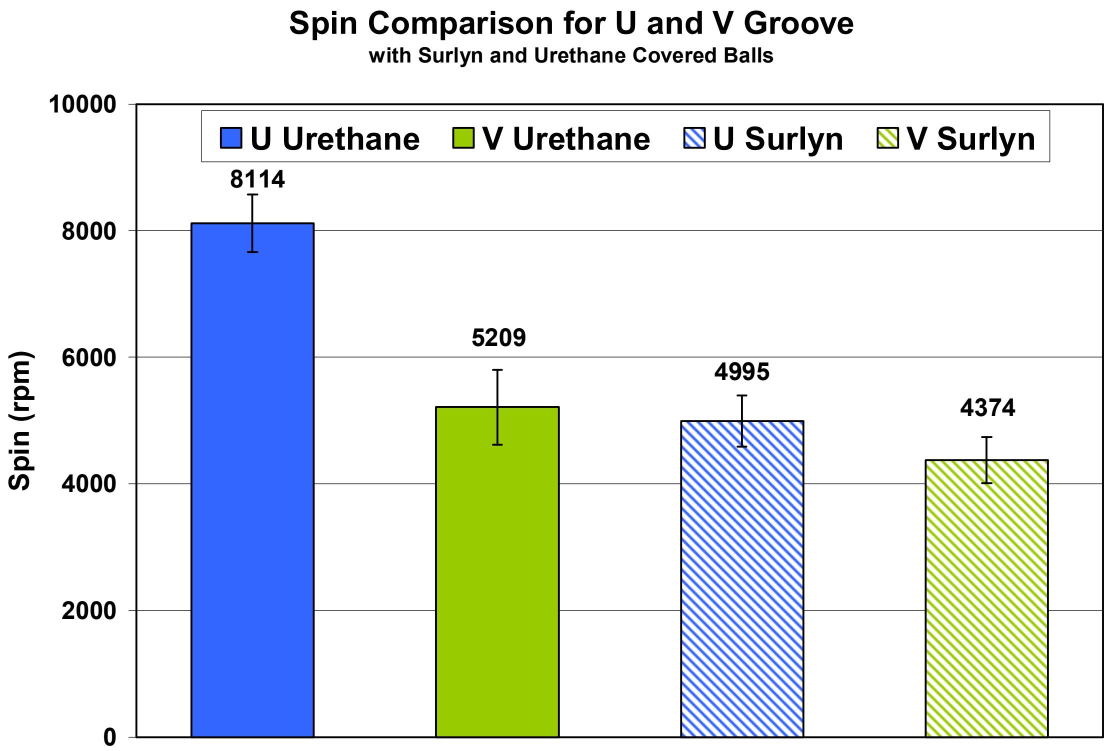


Figure 5 Comparison of amateur player average spin values for urethane and Surlyn covered balls.

CONCLUSIONS

The main objectives of this set of experiments were to determine if there was a discernable difference in spin performance between the U- and V-grooved clubs in the hands of amateur golfers out of the light rough, and to determine if the spin performance was ball cover material dependent. The test results demonstrated that there is an appreciable difference in spin rate achieved with amateur players using U-grooved clubs with urethane covered balls over spin rates with V-grooved clubs. The U-groove club and urethane covered ball combination consistently achieved higher spin rates, and this was most apparent at the 8 iron loft. The second portion of these tests demonstrated that there is only minimal difference in spin rates achieved by amateur golfers when using U- and V-grooved clubs in combination with Surlyn covered balls. These tests go even further to demonstrate that the spin performance of a urethane covered ball in concert with a V-groove has very little advantage over a Surlyn covered ball and either groove configuration.