

Article

The Aerodynamics of New Design Soccer Balls Using a Three-Dimensional Printer

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Featured Application: Wind-tunnel tests of 3D-printed soccer balls with various surface features are used to create an equation that predicts the critical Reynolds number.

Abstract: Eight balls were manufactured with a 3D printer to resemble various types of 32-panel soccer balls. One ball was completely smooth, whereas the other seven possessed various dimple patterns on their surface panels. Seam width and seam depth were also varied. Wind-tunnel experiments were performed to extract aerodynamic coefficients, and also to determine the critical Reynolds number for each manufactured ball. A new surface roughness parameter is introduced, and a fitting formula is presented, which allows for the prediction of the critical Reynolds number if the new parameter is known.

Keywords: three-dimensional printer; dimple; seam; protrusion; World Cup; aerodynamics; soccer; association football; wind tunnel



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1. Introduction

Soccer balls have changed considerably from the traditional 32-panel ball, which consisted of 20 regular hexagonal panels and 12 regular pentagonal panels. The panels in those traditional balls were arranged as in a truncated icosahedron. When Adidas unveiled the Teamgeist ball for the 2006 World Cup in Germany, a ball with 14 panels, a new era of soccer ball design began. The number of panels on World Cup soccer balls then dropped to eight for the Jabulani ball used in South Africa for the 2010 World Cup, and then to six for both the Brazuca ball used in Brazil for the 2014 World Cup and the Telstar 18 ball used in Russia for the 2018 World Cup. The Europass ball that was introduced for the UEFA Euro 2008 had a prestressed concrete (PSC) creeps surface design. That ball's surface was roughened with various protrusions, such as squares, triangles, and hexagons. The Al Rihla and Oceanz balls, used for the 2022 men's World Cup in Qatar and 2023 women's World Cup in Australia and New Zealand, respectively, each possessed 20 panels.

Previous studies [1–12] reported on the effects of surface properties on a ball's aerodynamics and flight trajectory. Other studies [13,14] evaluated and assessed the variations on aerodynamics and flight properties due to changes in the panel orientation that are attributed to the reduced number of panels. Research on how the number of panels, shape of surface structures (convexity and concavity), and surface design (such as protrusions) of modern soccer balls affect their aerodynamic properties have been published [15].

Three-dimensional printing is a technique that fabricates complex structures and geometries from 3D model data. The performance of 3D printers has improved significantly in recent years, allowing 3D printers to be used extensively in the research and development of modern sports equipment [16–23]. Studies on the dimple structures on golf balls using 3D printers have also been conducted [24–26].

Surface materials used in the construction of soccer balls vary greatly between ball types and manufacturers. Seam structures between panels may be machine-stitched, hand-stitched, or thermally bonded, and panels may be smooth or textured; those features are found to influence the aerodynamic characteristics of soccer balls [3,8]. There does not appear to be a canonical parameter that researchers use to characterize surface features. For this study, eight 32-panel soccer balls with various surface features, such as differing dimple structures, were created using the same material, polyamide-12, with a 3D printer. Computer-printed soccer balls allow for the creation of controllable surface variations. Computer-determined areas of smooth and roughened parts of balls are much more easily found than with real soccer balls.

After fabricating the soccer balls, their associated aerodynamic parameters were determined with wind tunnel experiments. Though the current study determined side and lift coefficients, which could potentially extend the previously published work [27] on manufactured dimpled soccer balls, those coefficients will not be presented here because of a desire to keep a tight focus on the correlation between surface roughness and critical Reynolds number. To build on what is known about how a soccer ball's surface influences its aerodynamic coefficients, this study introduces a new surface parameter that determines a soccer ball's critical Reynolds number. The critical Reynolds number is the Reynolds number associated with the minimum in the drag coefficient. That minimum occurs when separation of the boundary layer of air transitions from turbulent to laminar as the air's flow speed is reduced.

Parameterizing surface roughness is challenging because of the myriad ways in which a surface may deviate from being smooth. Efforts to do so date back half a century to the seminal work performed by Achenbach [28]. The roughness parameter used in that work was essentially a ratio of a dimension associated with surface asperity to sphere diameter. Building on that work a decade later, Mehta's classic review [29] referred to roughness in mostly qualitative ways, but did mention roughness height: be it positive, as with a pimple; or negative, as with a dimple. The limiting nature of the aforementioned surface parameter, and its inability to be a good predictor of the critical Reynolds number, led to other surface characterizations, such as more recent work on sports balls [30]. That work introduced a criterion for roughness that was based on statistical measures often found in tribology. Though the criterion introduced in that work did a better job predicting the critical Reynolds number, the hope here is that the parameter introduced in this current work will be simpler to use and evaluate.

The aim of the current study was not to replicate a modern soccer ball, but to start with the classic 32-panel design, and then vary panel roughness in a controlled way so that a new parameter could be found that would allow for the prediction of a ball's critical Reynolds number.

2. Materials and Methods

The following subsections describe the creation of balls in a 3D printer, the parameters that characterize the surface properties of the manufactured balls, and the wind tunnel experiments performed with the balls.

2.1. Soccer Ball Production

Eight spherical balls with diameter 22 cm were fabricated using polyamide-12 on a Jet Fusion 4200 3D printer from Hewlett Packard. One ball was designed to be smooth, but had a few small irregularities [31]; the other seven balls possessed the 32-panel surface of a traditional soccer ball. The surfaces of the balls were coated with graphite, which helped to smooth ball surfaces that contained small irregularities from the printing process. The target mass of each ball was set at 450 g, the maximum mass of a regulation soccer ball. The 3D printing process, however, created balls with approximately 4% greater average mass than the aforementioned set amount. Aerodynamic forces do not depend on ball mass,

but an effort was made to print balls that were physically similar to the actual soccer balls tested in the authors' wind tunnel during the past several years.

Surface designs for the fabricated soccer balls were created using 3D CAD software (Autodesk Inventor Professional 2020, Autodesk Inc., San Francisco, CA, USA). Photos of the manufactured balls, each with a unique surface, are shown in Figure 1. The eight balls are labeled A–H and are described as follows (balls B–H all have 32 panels): (A) a smooth ball, (B) a ball with seams and smooth panels, (C) a ball with conical dimples, (D) a ball with spherical dimples, (E) a ball with cylindrical dimples, (F) a ball with approximately half the number of conical dimples as on ball C, (G) a ball with approximately one quarter the number of conical dimples as on ball C, and (H) a conical dimpled ball like ball C, but with five times deeper seams.

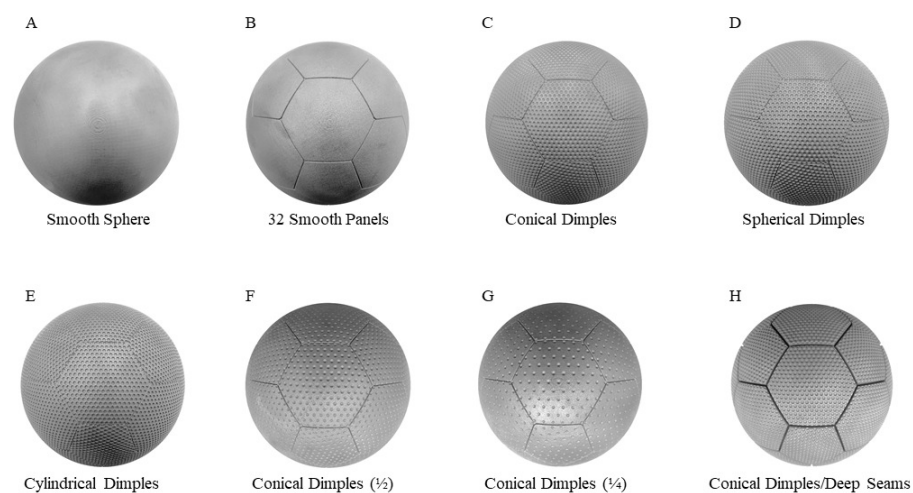


Figure 1. Eight balls manufactured by 3D printer.

Various parameters needed to characterize the surface textures on the manufactured balls were determined from the CAD software. It was not possible to make accurate physical measurements of the surface properties of the printed balls, a possible limitation of this study. The 3D CAD software did, however, produce surface features possessing sizes that were consistent with measurements made using rudimentary tools. The parameters that describe the dimples are the number of dimples, n , the distance between neighboring dimples, b , dimple width, c , and dimple depth, k . The latter three parameters are illustrated schematically (not to scale) in Figure 2 for the three types of dimples studied in this investigation.

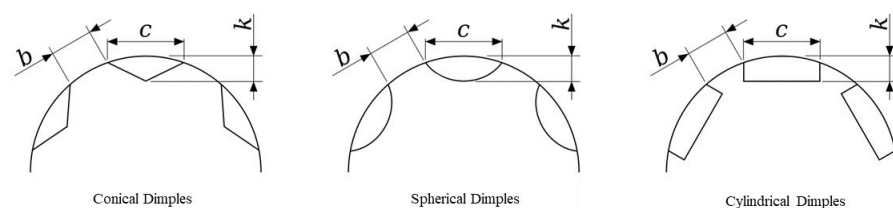


Figure 2. Schematic illustration (not to scale) of the distance between neighboring dimples, b , dimple width, c , and dimple depth, k , for the three types of dimples on six of the manufactured balls.

For the seams, radius of curvature, r_s , seam width, c_s , and seam depth, k_s , are needed for characterization. Figure 3 illustrates schematically (not to scale) the aforementioned three seam parameters.

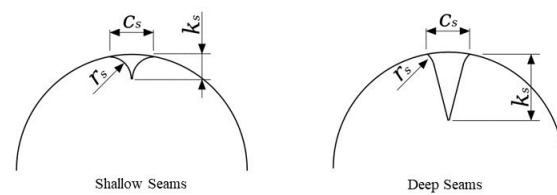


Figure 3. Schematic illustration (not to scale) of the radius of curvature, r_s , seam width, c_s , and seam depth, k_s , for seven of the manufactured balls.

Table 1 summarizes the properties of the fabricated balls. The table contains the type of seam (shallow or deep), the dimple shape (none, conical, spherical, or cylindrical), the previously described dimple parameters (n , c , and k), the previously described seam parameters (r_s , c_s , and k_s), the total seam area (A_s), and ball mass (m). The total seam area is the entire surface area of the seams, which is comprised of the areas of the seam sides and seam bottoms. From a smooth ball, to a ball that simulates a traditional 32-panel soccer ball, to balls with narrow and shallow seams, to a ball with deep and wide seams, to three different conical dimple counts, there is enough variation in surface type to tease out the way in which surface parameters impact ball aerodynamics.

Table 1. Properties of fabricated soccer balls: ball label from Figure 1, seam type, dimple shape (DS), number of dimples (n), distance between dimples (b , in mm), dimple width (c , in mm), dimple depth (k , in mm), seam radius of curvature (r_s , in mm), seam width (c_s , in mm), seam depth (k_s , in mm), total seam area (A_s , in cm^2), and mass (m , in g).

Ball	Seam	DS	n	b	c	k	r_s	c_s	k_s	A_s	m
A										0.000	465
B	shallow						1.0	2.063	1.0	102.6	472
C	shallow	conical	9344	1.415	3.0	1.0	1.0	2.063	1.0	102.6	466
D	shallow	spherical	9344	1.415	3.0	1.0	1.0	2.063	1.0	102.6	470
E	shallow	cylindrical	9344	1.415	3.0	1.0	1.0	2.063	1.0	102.6	460
F	shallow	conical (1/2)	4760	3.168	3.0	1.0	1.0	2.063	1.0	102.6	469
G	shallow	conical (1/4)	2504	5.637	3.0	1.0	1.0	2.063	1.0	102.6	468
H	deep	conical	9344	1.415	3.0	1.0	1.0	5.367	5.0	431.6	473

A study like the one described in this paper is always susceptible to criticism for not having enough variety in the ball surface features. The response to such justified criticism focuses solely on cost. The total cost for each ball fabricated in the 3D printer is \$2000 (US). That cost includes materials, printing fees, and the expense associated with personnel who run and maintain the 3D printer. The manufacturing and testing of eight balls exhausted the available budget for this study. Because each ball must be destroyed when the sting is inserted for wind-tunnel testing, investigation was limited to one ball orientation, that shown in Figure 1 (imagine the air flowing into the photo, striking the ball with the unseen sting mount in the back). This paper's authors claim that there is significant enough variety in ball surface, given the available research budget, that the results provided in this work are both meaningful and novel.

2.2. Wind Tunnel Experiment

Wind tunnel experiments were conducted at the University of Tsukuba using a circulatory, low-speed, low-turbulence wind tunnel (San Technologies Co., Ltd., San Diego, CA, USA). Figure 4 shows one of the manufactured balls mounted on a sting in the wind tunnel. The sting was inserted where the hole that began the printing process was located, which meant that the support location for 3D printing was covered by the sting and thus did not adversely affect wind-tunnel measurements.

The maximum wind speed is approximately 55 m/s (198 kph or 123 mph) with a jet size of 1.5 m $\times$ 1.5 m, a wind speed distribution within $\pm 0.5\%$, and a turbulence of less

than 0.1%. The wind speed, v , was varied from 7 m/s to 30 m/s, taking two sets of force measurements at 1-m/s intervals. Each force measurement lasted for 5 s. Because data were taken at the rate of 100 Hz, there were 500 force measurements taken in the 5-s interval. Given the two sets of force measurements, there were a total of 1000 force measurements. An average and standard deviation could be obtained from those 1000 force measurements. All measurements were performed in the temperature range 22 °C–30 °C. Temperature variation occurred because of time of day when experiments were performed.



Figure 4. Wind tunnel experimental setup.

The aerodynamic forces acting on the manufactured balls were measured using a sting-type, six-component force detector (LMC-61256, Nissho Electric Works, Osaka, Japan). The force on the ball in the direction of the air flow is the drag force, $\vec{F}_D$; the force in the horizontal direction, perpendicular to the air flow is the side force, $\vec{F}_S$; and the vertical force is the lift force, $\vec{F}_L$. The dimensionless aerodynamic coefficients extracted from the force data were the drag coefficient, C_D , the side coefficient, C_S , and the lift coefficient, C_L . Those coefficients are contained in expressions for the magnitudes of the drag force, side force, and lift force, given by [32]:

$$F_D = \frac{1}{2} C_D \rho A v^2, \quad (1)$$

$$F_S = \frac{1}{2} C_S \rho A v^2, \quad (2)$$

and

$$F_L = \frac{1}{2} C_L \rho A v^2, \quad (3)$$

respectively, where $\rho \simeq 1.2 \text{ kg/m}^3$ is the air density, which can vary slightly with temperature [32], and $A \simeq 0.038 \text{ m}^2$ is the cross-sectional area of a ball.

Taking data for longer time intervals did not significantly alter the average force. Two measurements provided the opportunity to see how much fluctuation there was in measurements. As will be seen shortly, drag forces did not vary appreciably. Side and lift forces, however, had a bit more variation, especially at high speeds, because those forces were close to zero. Ball surface, slight fluctuations in air flow, and even—though to a lesser

extent—the rear-mounted sting, contributed to an asymmetric shedding of the boundary layer off the ball. That asymmetric shedding gives rise to the side and lift forces on a non-spinning soccer ball.

Though trajectory analysis will not be presented in this paper, a bit more context will be provided to illustrate how Equations (1)–(3), along with this work’s wind tunnel results, may be used to determine the trajectory of a soccer ball in flight above the pitch. The brief aside that concludes this subsection will allow for the introduction of the Reynolds number.

The equation of motion for a soccer ball’s center of mass in flight is

$$m \frac{d^2 \vec{r}(t)}{dt^2} = \vec{F}_D + \vec{F}_S + \vec{F}_L + m \vec{g}, \quad (4)$$

where m is the ball’s mass, $\vec{r}(t)$ is the position vector for the ball’s center of mass in some predetermined coordinate system, and $\vec{g}$ is the downward-pointing acceleration due to gravity with magnitude 9.8 m/s^2 that is used for the ball’s weight, $m \vec{g}$. The force from the air has been split into three orthogonal components, $\vec{F}_D$, $\vec{F}_S$, and $\vec{F}_L$, whose magnitudes are given in Equations (1), (2) and (3), respectively. The drag force points opposite the ball’s velocity at all times, the side force is perpendicular to the plane formed by the ball’s velocity and the ball’s weight, and the lift force is perpendicular to the ball’s velocity and in the plane formed by the ball’s velocity and the ball’s weight. Though the air’s buoyant force is easy to include, that force is less than 2% of a soccer ball’s weight. More mathematical and computational details, such as how to express Equation (4) in Cartesian coordinates, may be found elsewhere [33].

The numerical solution of Equation (4) requires the speed-dependent aerodynamic coefficients, C_D , C_S , and C_L . The previous section described how those coefficients are found via wind tunnel experiments. For speeds not measured in the wind tunnel, linear interpolation may be used to create values of the aerodynamic coefficients for any speed between 7 m/s and 30 m/s. Because the aerodynamic coefficients were determined for ball orientations shown in Figure 1, trajectories determined computationally must assume a non-spinning ball launched in the wind-tunnel-tested orientation.

The Reynolds number must be converted to speed so that the aerodynamic coefficients may be made dependent on speed. The Reynolds number, Re , is defined as [32]:

$$Re = \frac{v D}{\nu}, \quad (5)$$

where v is ball speed, D is a ball’s diameter, and $\nu = \mu/\rho$ is the kinematic viscosity, where μ is the viscosity. During a given wind tunnel test, the Reynolds number was determined by Equation (5) using the wind tunnel’s flow speed and the appropriate value of the kinematic viscosity of air at a pressure of 1 atm and at the temperature recorded during the experiment. In the middle of the temperature range where experimenting took place, i.e., at 26°C , the kinematic viscosity for air at a pressure of 1 atm is $1.55 \times 10^{-5} \text{ m}^2/\text{s}$ [32]. Numerical solutions for trajectories that assume the same 26°C temperature will convert the Reynolds number to speed using $v \simeq (7.05 \times 10^{-5} \text{ m/s}) \cdot Re$. Temperature fluctuations in the range where testing was performed were responsible for the kinematic viscosity’s 5.5% increase from its low-temperature value to its high-temperature value [32].

3. Results and Discussion

After presenting wind tunnel results, a correlation analysis of surface properties and the critical Reynolds number will be presented.

3.1. Wind Tunnel Data

Figure 5 shows drag coefficients for the eight manufactured balls as functions of the Reynolds number. To provide a comparison with an actual soccer ball, drag coefficient data from a previous investigation [6] for Telstar 18, which was used during the 2018 World Cup in Russia, are included in Figure 5. Points in Figure 5 are average values of 1000 force

measurements at the various wind tunnel speeds. Error bars show one standard deviation on each side of the average. Because no wind tunnel is capable of creating a perfect flow of air in which every small cross section of area within the wind stream has the same time-independent flow velocity, force measurements vary slightly from one trial to the next. What the error bars in Figure 5 thus provide are rough estimates for sizes of variations in drag coefficient caused by inhomogeneities in wind tunnel flow. Horizontal error bars would be much smaller than the vertical ones because determining air-flow speed is much more accurate than deducing a drag coefficient from averaged force data.

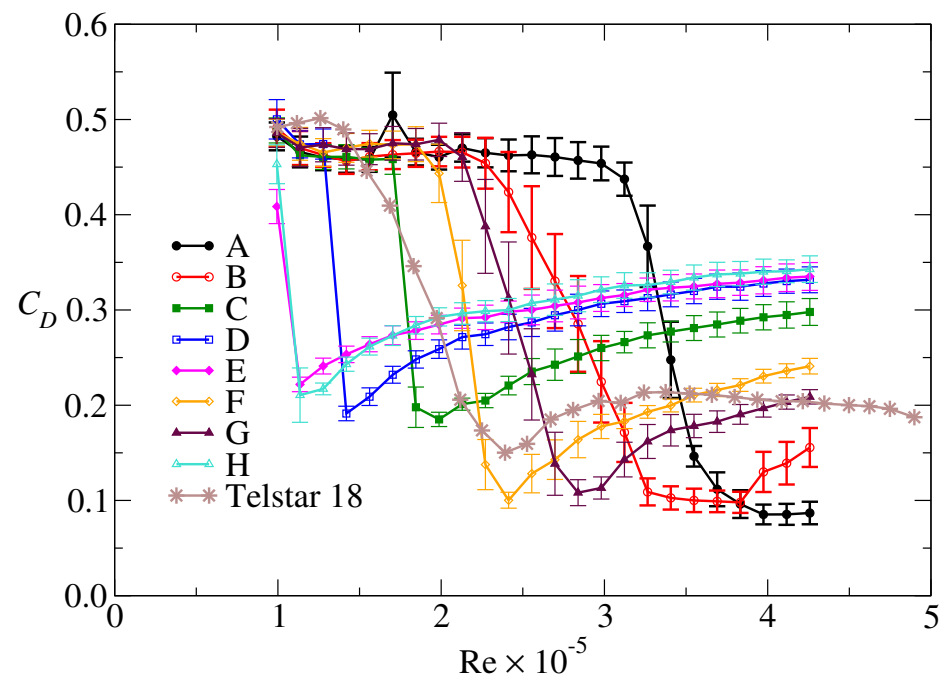


Figure 5. Drag coefficients of manufactured balls versus Reynolds number. Also shown for comparison are drag data for an actual soccer ball, the Telstar 18 [6].

Drag coefficient data in Figure 5 follow the now-familiar trend [28,30] that making a ball's surface rougher leads to a smaller critical Reynolds number and a larger drag coefficient at that critical Reynolds number. Table 2 lists the critical Reynolds numbers and corresponding drag coefficients for the eight manufactured balls and the Telstar 18.

Table 2. Critical Reynolds number and corresponding drag coefficient for each of the manufactured balls and for Telstar 18.

Ball	$Re_c \times 10^{-5}$	$C_D (Re_c)$
A	3.97	0.085
B	3.83	0.098
C	1.99	0.185
D	1.42	0.191
E	1.14	0.222
F	2.41	0.100
G	2.84	0.108
H	1.14	0.211
Telstar 18	2.39	0.150

The critical Reynolds number and corresponding drag coefficient for ball A match quite well with what Achenbach reported in his classic paper dealing with aerodynamics of smooth spheres [34], even though the minimum in ball A's C_D is admittedly at the third largest measured speed. Ball B's minimum C_D is easily identified, but Figure 5 shows that

there is not as much curvature at the location of the minimum as there is for the other printed balls.

Ball B is modeled after a traditional 32-panel soccer ball. Numerous companies produce many types of 32-panel soccer balls with various ways of connecting the seams. Compared to the Molten Vantaggio [35], a 32-panel soccer ball with thermally bonded panel edges, ball B's critical Reynolds number is approximately 13% larger and its corresponding drag coefficient is about 41% smaller. The manufactured 32-panel ball is smoother than the Vantaggio soccer ball, with ball B's seams not as wide and deep as those between Vantaggio's thermally bonded panels. That explains why ball B has a larger critical Reynolds number compared to Vantaggio's.

The Telstar 18 drag coefficient data fall somewhere between balls C and F for $Re < Re_c$, but look to be closer to ball F, and perhaps ball G, for $Re > Re_c$. Recall that balls C, F, and G all have conical dimples on their surfaces. The aerodynamics of a modern soccer ball may then be similar to a 3D-printed 32-panel ball with conical dimples. Such a proposition's validity will need more study to demonstrate.

Because the focus of this work is on the connection between a ball's surface roughness and the critical Reynolds number, wind tunnel data for the side and lift forces will not be shown. There are certainly interesting fluctuations in C_S and C_L about zero, reflecting asymmetric shedding of the boundary layer of air off the back of the balls, but the desire for a tight focus here will move the display of that data to a possible future publication.

The wind tunnel drag coefficient data displayed in this section are consistent with those of real soccer balls [3,4,6,9]. There is thus confidence that the surfaces produced on the 3D-printed balls lead to aerodynamic properties consistent with actual soccer balls. Aerodynamic data are also similar to what previous studies have reported for golf balls [25,36–40].

3.2. Correlation Analyses

There are several ways to characterize the roughness of the balls manufactured for this study. Dimple count could be used, but ball B, with its smooth panels, has seams that influence the ball's aerodynamic properties. Seam length could be used, but that parameter will not account for ball H's deeper seams. Dimple depth alone neither considers how many dimples are on a ball's surface nor the shape of those dimples.

To account for the various ways a ball's surface may be roughened, surface roughness is measured here by forming a ratio of the new surface area created by the dimples and seams to the surface area of the remaining original surface. Because dimples and seams are carved into the ball's surface, the sum of the carved dimple and seam area exceeds the difference of a smooth ball's surface area and the remaining smooth surface area. The ratios formed here will thus not all have the same denominator.

The starting surface area is that of smooth ball A, which has a surface area of $A_{surface} = \pi (220 \text{ mm})^2 \simeq 152,053 \text{ mm}^2$. The areas of all the dimples and seams were determined using the same 3D CAD software that created those surface features for the manufactured balls. Table 3 lists the software-measured areas, rounded to the nearest mm^2 , of all the dimples on a ball, $A_{dimples}$, of all the seams on a ball, A_{seams} , and of all the remaining smooth portions on a ball, A_{smooth} . Also listed in Table 3 are the ratios of total dimple surface area to total smooth surface area, $\eta_d = A_{dimples}/A_{smooth}$, and total surface area of dimples and seams to total smooth surface area, $\eta_{ds} = (A_{dimples} + A_{seams})/A_{smooth}$.

The critical Reynolds number is more strongly correlated with η_{ds} than with η_d . The parameter η_{ds} is clearly more representative of a ball's surface roughness because both dimples and seams are accounted for. Note that $\eta_d = 0$ for both balls A and B because neither ball was manufactured with dimples. But ball B's seams are responsible for a rougher surface than smooth ball A and, as Table 2 shows, a smaller critical Reynolds number than that of ball A.

Table 3. Software-determined total dimple surface area, $A_{dimples}$; total seam surface area, A_{seams} ; total smooth surface area, A_{smooth} ; and the ratios $\eta_d = A_{dimples}/A_{smooth}$ and $\eta_{ds} = (A_{dimples} + A_{seams})/A_{smooth}$. All areas are in mm².

Ball	$A_{dimples}$	A_{seams}	A_{smooth}	η_d	η_{ds}
A	0	0	152,053	0.0000	0.0000
B	0	10,264	143,948	0.0000	0.0713
C	78,891	10,264	79,894	0.9875	1.1159
D	96,626	10,264	79,894	1.2094	1.3379
E	153,214	10,264	79,894	1.9177	2.0462
F	40,189	10,264	112,143	0.3584	0.4499
G	21,141	10,264	127,169	0.1662	0.2470
H	78,891	43,161	74,610	1.0574	1.6359

A three-parameter fit was determined for the functional dependence of Re_c on η_{ds} . The fitting equation is

$$Re_c \times 10^{-5} = \alpha \exp(-\beta \eta_{ds}^N) \quad (6)$$

with fitting parameters $\alpha = 4.06 \pm 0.15$, $\beta = 0.81 \pm 0.06$, and $N = 0.70 \pm 0.01$. The errors in the fitting parameters are standard errors, i.e., standard deviations, in a nonlinear model fit. Figure 6 shows the data with Equation (6). All three parameters have a p value of $p < 10^{-4}$ and the quality of the fit is such that $R^2 = 0.995$.

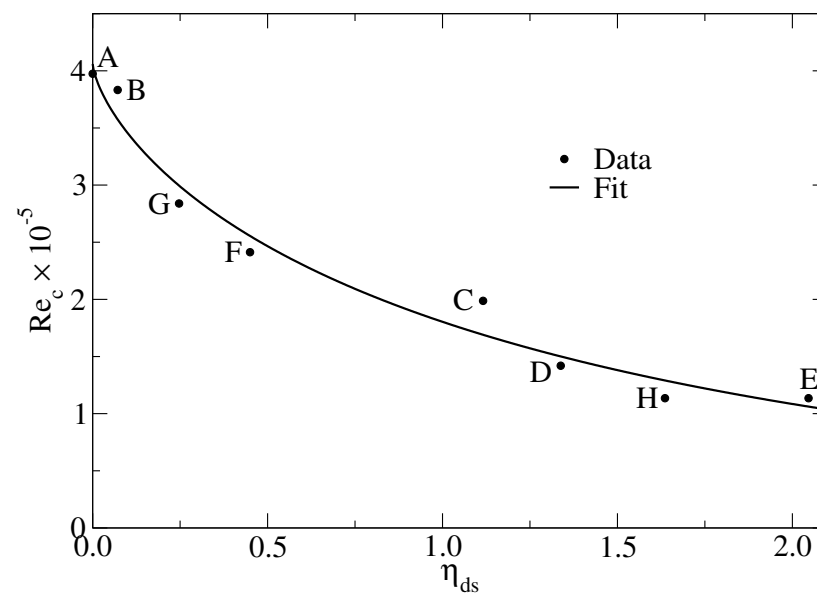


Figure 6. Comparison between data and fitting equation, given by Equation (6). Letters next to points correspond to the ball labels given in Figure 1.

The parameter $\eta_{ds} = (A_{dimples} + A_{seams})/A_{smooth}$, which accounts for the roughness of a ball's surface, is thus an excellent parameter to use as a predictor for one of the manufactured ball's critical Reynolds number. To test the accuracy of Equation (6), a method will need to be devised to accurately determine η_{ds} for a real soccer ball.

One study [3] showed that the critical Reynolds number was more strongly correlated with seam width than with seam depth. That work's conclusion is consistent with what has been shown here, namely that the critical Reynolds number depends strongly on the fraction of surface area that comprises rough features, such as seams and dimples, to the remaining smooth surface area. Increasing seam width does more to add roughness and remove smoothness than simply increasing the depth of a seam.

4. Conclusions

The results presented in the previous section show that the critical Reynolds numbers of the manufactured soccer balls depend strongly on a ball's surface dimple structure and seam characteristics. Teasing out the physics behind how a ball's surface properties influence the critical Reynolds number may be performed in a couple of ways. More balls could be printed with various other seam depths, seam widths, and panel features. Such an effort would allow for more data to populate Fig. 6 and could provide enough new data to make a definitive determination of whether, for example, the critical Reynolds number depends more strongly on seam width than on seam depth. The drawback to printing and testing more balls is cost.

Because aerodynamic forces on a soccer ball do not depend on ball mass, 3D-printed balls possessing the same diameter as real soccer balls allowed researchers in this study to vary surface roughness in a controlled way, and then extract aerodynamic coefficients associated with each manufactured ball. The new surface roughness parameter introduced here, when used with an empirically determined fitting equation, was shown to predict the critical Reynolds numbers for all tested balls, ranging from completely smooth to considerably rough.

More research will have to be performed to see if the surface roughness parameter introduced here predicts critical Reynolds numbers for various types of real soccer balls as well as it did for the 3D-printed, 32-panel balls used in this work. Three-dimensional laser scanning of real soccer balls could be one technique used to determine the parameter necessary to predict the critical Reynolds number. Further work with 3D printing may also be performed, but, as previously noted, cost will be a limiting factor. Balls with the same value of the new roughness parameter could be created, but with seam and panel surface features different from those used in this study. Pimples could be printed instead of dimples. The options for what could be printed are essentially endless.

Another approach is to employ the techniques of computational fluid dynamics (CFD). This paper's authors are currently involved in such an effort. CAD files used for the 3D printing process are now being used as the basis for a CFD study. Once that undertaking is completed, the CFD results will be analyzed with the hope that how the specific surface features affect a ball's critical Reynolds number will be revealed. The results of that endeavor will be the subject of a future publication.

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