

Influence of Geometric Shapes of Parts on 3D Scanning Accuracy for Reverse Engineering

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ABSTRACT

This paper investigates the geometric shapes of parts on 3D scanning for reverse engineering. The aim was to develop guidelines for scanner settings with various shapes. Five different geometric shapes were scanned and compared for surface detail reproduction across More details, Standard details, and Less details settings. GOM Inspect software compared standard triangle language files, point clouds, and polygon meshes. The results showed that different geometries lead to different point clouds and surface details after scanning. Point clouds generated with the More details setting are a substantially larger amount compared to those generated using the Standard detail and Less details settings. The mesh size exhibits an inverse relationship with point cloud data. A reduction number of point clouds corresponds to an increase in mesh size. Geometric shapes of triangle, cone, cubic, and sphere can be created with the standard detail, while geometric shape of cylinder requires less details for optimal scanner settings. The reverse deep-drawing of cups was an example demonstrating the benefits of the developed guidelines to show the curved part that is often a problem for the industry and causes thickness variation and tearing during forming. A comparative analysis of the reverse deep-drawing of cups utilized standard details compared with the computer-aided design file. Errors were minimal on the smooth surface, largely within ± 0.10 mm. The nose radius of the cups presented an error range of approximately ± 0.200 mm. When tested with a die created using high drawing speed, the improved nose radius was found to be in the range of 0.470 to 0.480 ± 0.014 mm.

Keywords: Geometric shapes, 3D scan, Point clouds, Polygon meshes, Reverse engineering

1. INTRODUCTION

Three-dimensional (3D) scanning has become an important technology for acquiring the shape and dimensions of physical objects. This technology, employing non-contact measurement techniques, is adapted for applications in reverse engineering, quality control, and rapid prototyping. A method that can capture intricate surface details and complex geometries has revolutionized various industries, offering enhanced flexibility and reliability in measurement, analysis, and storage [1]. Reverse engineering is a technique used to create three-dimensional models of physical objects. 3D measurement devices are employed in this process. When no technical drawings, scanning the object becomes necessary to obtain a 3D model. The resulting model is then digitized and refined using software before being used for production [2]. However, the accuracy and reliability of scanning are influenced by numerous factors, including the scanner calibration, environmental conditions, surface properties of the object, and the scanning parameters [3]. One of the primary factors influencing the accuracy of 3D scanning is the geometric characteristics of the object being scanned [4]. The shape, size, and complexity of the object can significantly impact the quality of the scanned data [5]. Objects with intricate geometries, such as sharp edges, deep cavities, and complex curvatures, pose challenges for optical scanners due to occlusions, reflections, and variations leading to inaccurate measurements. To address these challenges, optimizing scanning parameters can help mitigate the effects of reflections and variations in surface normals, enhancing the accuracy and reliability of the scanned data [6].

Geometric features introduced inaccuracies in 3D scanning due to several contributing factors. Specifically, corners and edges, characterized by abrupt shifts in surface orientation, induced diffraction and scattering of the projected light, thereby compromising the precision of the resultant measured point cloud [7]. Surface properties, including color, texture, and reflectivity, profoundly affect optical 3D scanning outcomes. Dark or absorbent surfaces may not reflect sufficient light back to the sensor, leading to data loss or increased noise. Highly reflective surfaces can cause specular reflections, distorting the scanned data and creating inaccuracies [8]. Rough or textured surfaces may

scatter the projected light, reducing accuracy, while smooth, matte surfaces generally produce better results. Addressing these surface property-related challenges involves a multifaceted approach, incorporating techniques such as applying temporary, diffuse coatings to alter reflectivity, employing specialized scanning technologies less susceptible to surface variations, and optimizing scanning parameters to enhance data acquisition quality [9]. Environmental conditions during scanning substantially influence data quality. Ambient light can interfere with the structured light or laser patterns projected by the scanner, causing noise and reducing accuracy [10]. Thus, the environmental conditions effect on the raw data obtained from 3D scanners often contains noise, outliers, and missing points [11].

The density and distribution of points in a point cloud are intricately linked to the geometric attributes of the scanned object. Curved surfaces often exhibit varying point densities due to the changing angle of incidence of the projected light or laser beam, with areas perpendicular to the scanner yielding higher densities compared to oblique regions [11]. Sharp edges and corners present unique challenges, as the scanner resolution and accuracy limitations may result in rounded or blurred representations. Additionally, intricate and complex geometries can lead to occlusions, where certain surface areas are hidden from the scanner line of sight, causing gaps or missing data in the resultant point cloud. Compressing the measured point data while maintaining the required accuracy is a crucial task during the scanning measurement process [12]. The geometric characteristics of the scanned object significantly influence the creation of polygon meshes from point clouds. Subdivision surfaces provide a compressed shape representation well suited to shape analysis. A method to estimate a subdivision surface from the triangular meshes common in shape analysis [13]. The accurate reconstruction of sharp edges and corners in polygon meshes may require the use of sophisticated algorithms. Moreover, areas with high curvature or intricate details may require adaptive meshing techniques to ensure that the mesh accurately captures the object geometric complexity. This is achieved by refining the mesh density in regions of high detail while maintaining a coarser mesh in flatter areas

[14]. Objects with intricate surface textures or fine geometric features necessitate a high-resolution mesh with a large number of polygons to accurately represent these details. However, employing a high-resolution mesh for simple shapes can result in an unnecessarily large. Inversely, a low-resolution mesh for complex objects can lead to a loss of important geometric [15]. The occurrence of the surface “guessing” and deformed patches in the resulting 3D model during the scan [16]. The effect of geometric shapes on 3D scanning significantly affects data completeness [17]. Thus, geometric shapes of parts exert a considerable influence on the resultant point clouds and polygon meshes derived from 3D scanners [18]. The geometric shapes on 3D scanning for reverse engineering was investigated, focusing on scanning modes performed across five distinct geometric shapes. This approach facilitated a detailed comparison of surface reproduction across varying levels of detail: More Details, Standard Details, and Less Details. The analysis of STL files, point clouds, and polygon meshes was conducted using GOM Inspect software.

2. MATERIALS AND METHODS

The prototype workpieces were machined from medium carbon steel with different shapes, namely workpiece A (triangle), B (cone), C (cubic), D (sphere), and E (cylinder), as shown in figure 1. Before 3D scanning, AESUB, SKD-S2 spraying a coat on the object surface will help reduce the optical effects. GOM, ATOS Core 300 is used to scan workpieces. Technical parameters of ATOS scanner are in the table 1. Optical system calibration was subsequently performed utilizing a calibration object mounted on a rotary table. This calibration was instrumental in ensuring the dimensional consistency of the measuring system. The procedure adhered strictly to the recommended guidelines provided by the manufacturer, GOM GmbH. The computer controls the operation of the 3D scanner using a Dell Precision model M 4800. 3D scanning used for the three-dimensional measurement of objects parts combined with Gom Inspection software. The modes used for scanning parts include Matrix mode with surface data collection includes More details, Standard details, and Less details.

A comparison of the scanned details is performed to determine the mode and settings that are

appropriate for the prototype shape. The appropriate mode was selected, and experiments utilizing sample cup components from the industrial sector were conducted to evaluate the degree of deviation. Subsequently, design and create a deep drawing die of cups, test, and verify the results of the deep drawing process. Finally, inspect the thickness at different locations from the cross-section of the workpiece.

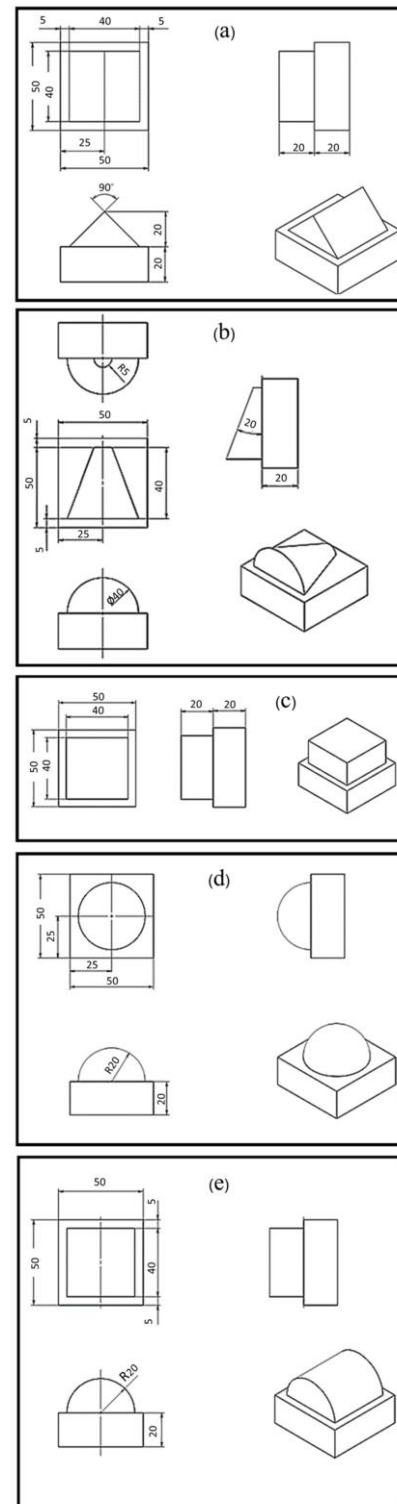


Figure 1 Workpiece shapes and drawing

Table 1 Parameters of 3D scanning

Parameters	Details
Measuring area	300 x 230 mm
Point Spacing	0.12 mm
Sensor Dimensions	361 x 205 x 64 mm
Camera resolution	5 million pixels
Working distance	440 mm
Angle between cameras	28 deg.

3. RESULTS AND DISCUSSION

A comparative evaluation of the scan results emphasizing surface details, point cloud data, and mesh data is provided for each workpiece in figures 2-6. The scanning results for workpiece A as presents in figure 2., revealing negligible differences in point cloud and mesh size between the Standard details and Less detailed settings. Conversely, employing the More detail configuration results in a greater quantity of point clouds and a reduction in mesh size.

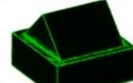
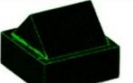
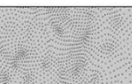
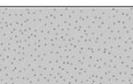
File	Surface Characteristics		
	More Details	Standard Details	Less Details
STL			
All Point Data			
Point Top - View			
Mesh Top - View			

Figure 2 Scan results of workpiece A.

Moreover, the presence of unorganized point clouds is noted at the edge and corner regions of the surface. Therefore, the utilization of Standard details and Less detailed settings yields satisfactory scan results for workpiece A. Workpiece B, geometry is a conical surface as depicted in figure 3. The point cloud distribution is uniform. Similar mesh sizes are observed for both More detail and Standard details settings, while the Less detailed setting exhibits the largest mesh size. Given the

enhanced texture reproduction, More detail and Standard details settings are recommended for this geometry.

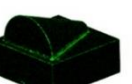
File	Surface Characteristics		
	More Details	Standard Details	Less Details
STL			
All Point Data			
Point Top - View			
Mesh Top - View			

Figure 3 Scan results of workpiece B.

In the case of workpiece C, as illustrated in figure 4. The More detail and Standard details' configurations led to the formation of unorganized point clouds. Conversely, the Less detailed setting produced a uniform and distributed arrangement of point clouds, and sufficient for scanning. According to the data presented in figure 5 (workpiece D), the More detail setting results in a higher concentration of point cloud data. The Standard detail setting yields a more even distribution, although some areas exhibit higher point density. However, the Less detail setting produces a uniformly distributed point cloud but is characterized by a larger mesh size. Workpiece E as depicted in figure 6. The More detail and Standard detail settings generated a distributed point cloud, which facilitated the creation of a fine mesh and complete surface coverage. Conversely, the Less detail setting resulted in a less dense point cloud and a coarser mesh, leading to the presence of numerous surface imperfections. The magnitude of point cloud data was directly proportional to the selected surface of detail during the scanning process. More detail settings correlated with a larger volume of point cloud data. Conversely, utilizing standard detail or less detail settings resulted in a lower point cloud density.

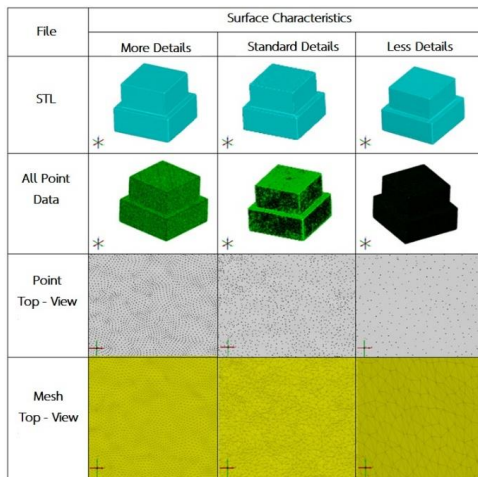


Figure 4 Scan results of workpiece C.

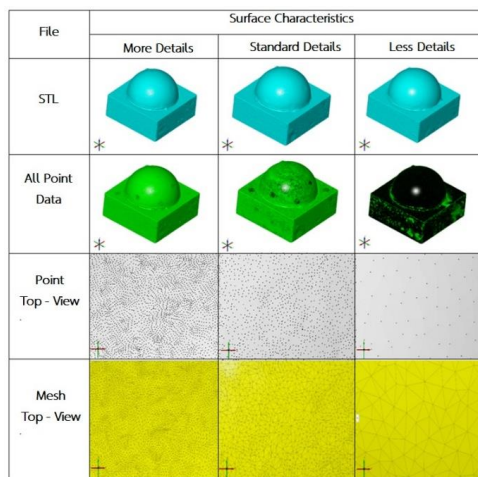


Figure 5 Scan results of workpiece D.

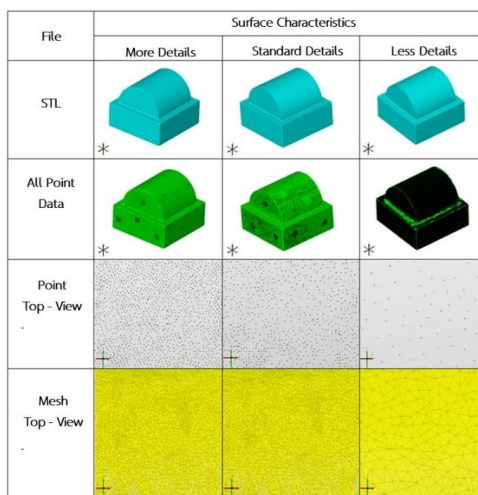


Figure 6 Scan results of workpiece E.

The results were compared point cloud data for all scan workpieces in figure 7. Workpiece D had a larger magnitude of point cloud data than the other part shapes in both modes of More details and Standard details. The Less detailed mode of all workpieces

showed almost identical point cloud data. Thus, the shapes are influenced by point cloud distribution because scanners transfer beams onto objects and receive them back. Point cloud reactions vary depending on the shape and surface types [19].

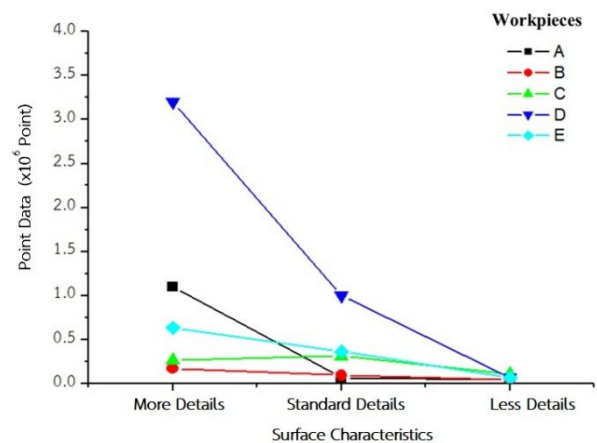


Figure 7 Point cloud data of workpieces.

Generally, the highest resolution during scanning was crucial, as low-resolution models often yielded poor detail quality, blurring smaller elements and only clearly displaying larger, basic components. Although higher resolution scanning facilitated the capture of finer details, this approach also resulted in larger datasets, thus augmenting the requirements for processing power and storage capacity. As a result, engineers were obliged to reconcile the necessity for detailed data with the practical limitations of data management.

During the scanning process, two categories of errors may arise. Accidental errors, stemming from unpredictable anomalies within the scanning system, lack a discernible pattern of occurrence. These errors manifest as outliers or pulse noise during 3D digitalization. In contrast, systematic errors follow predictable patterns arising from identifiable sources. These may include calibration methodologies, sensor sensitivity, attributes of the object under examination, ambient conditions, and the proficiency of the operator conducting the scan. The manifestation of such errors frequently involves the generation of spikes, which subsequently induce irregularities in the resultant curves and surfaces. Surface reconstruction is contingent upon the initial rectification of these errors via point cloud data preprocessing. Filtering, in this context, comprises

two essential operations: the removal of pulse noise and the smoothing of data-points. Post-filtering, the resultant point cloud often contains redundant data-points that can hinder processing efficiency and potentially introduce errors. Mitigating this involves employing techniques to reduce the prevalence of these superfluous data-points. Finally, geometric modeling and preprocessing of surfaces involve either surface approximation or polygonal approximation techniques. Typically, point cloud data undergoes a transformation into STL data file or triangular mesh models through a process known as surface reconstruction [20]. Consequently, point clouds often retain a degree of redundant data, exemplified by Workpieces B, C, and D. This redundancy primarily impedes and decelerates data processing, and in some instances, may introduce inaccuracies. Employing data reduction techniques can resolve this issue by eliminating superfluous data points.

However, the presence of irregularities in point distribution and mismatched alignments can occur in certain patterns, specifically observed in workpieces A, C, and D, when employing the More details scanning mode. These artifacts arise as a consequence of the intricate surface geometry of these workpieces, compounded by the inherent limitations of the optical scanning process [21]. The irregularities in point distribution stem from variations in surface reflectivity and local geometric features, which can lead to inconsistencies in the scanner ability to accurately capture data across the entire surface. This is particularly evident in regions with sharp edges, or complex curvatures, where the scanner's line of sight may be obstructed or the reflected light signal may be distorted. In addition to point distribution irregularities, mismatched alignments can also occur, particularly when the scanner struggles to maintain consistent registration between adjacent scan passes. When the laser scanner scans an object, it calculates the three-dimensional coordinates for each pixel on the object based on the principle of 3D triangulation, as it measures distance, angle, and height of the instrument provided by the user [22]. This phenomenon arises from subtle shifts in the scanner's position or orientation during the scanning process, as well as from accumulated errors in the scanner's internal calibration.

The completeness of a point cloud, which refers to the extent of digitizing gaps, and its accuracy, which is associated with the measurement uncertainty of a 3D point, serve as key indicators of point cloud quality. Moreover, the geometric properties of an object, specifically its dimensions and shape, introduce complexities in achieving uniform data density across the entire surface during optical 3D scanning. Shiny metallic surfaces present substantial challenges in the realm of optical 3D scanning due to their inherent reflective properties, which can lead to specular reflection instead of diffuse reflection [6]. While 3D scanning and point cloud data with even distribution points are orderly can lead to high-quality STL files and a 3D surface model. Table 2. presents scanning suggestions for different workpieces according to shape characteristics.

Table 2 Scanning suggestions for different workpieces

Workpieces	More Details	Standard Details	Less Details
A		✓	✓
B	✓	✓	
C			✓
D		✓	✓
E	✓	✓	

The Standard details mode is generally suitable for scanning all workpieces, except for workpiece C, which benefits from the Less details option. The More Details mode is specifically advantageous for tasks A and B. Conversely, the Less Details mode remains effective for workpieces A, C, and D. However, the case of mode Standard details that most users usually choose to use with the scanner. To quantitatively assess the accuracy of the scanning process, a deviation analysis was performed, comparing the resultant 3D model with the original CAD file. Based on the reverse engineering of the deep-drawing cup part utilizing Standard details. A comparison of the reverse engineering results with the drawing or CAD file, as shown in figure 8. indicates minimal error from scanning and modeling. This is supported by the color bands, where green indicates a difference of -0.1 to +0.1 mm. The curved or concave edge of the cup shows yellow and blue deviations up to ± 0.2 mm. However, deviations exceeding ± 0.2 mm or other colors were not apparent on the scanned workpieces.

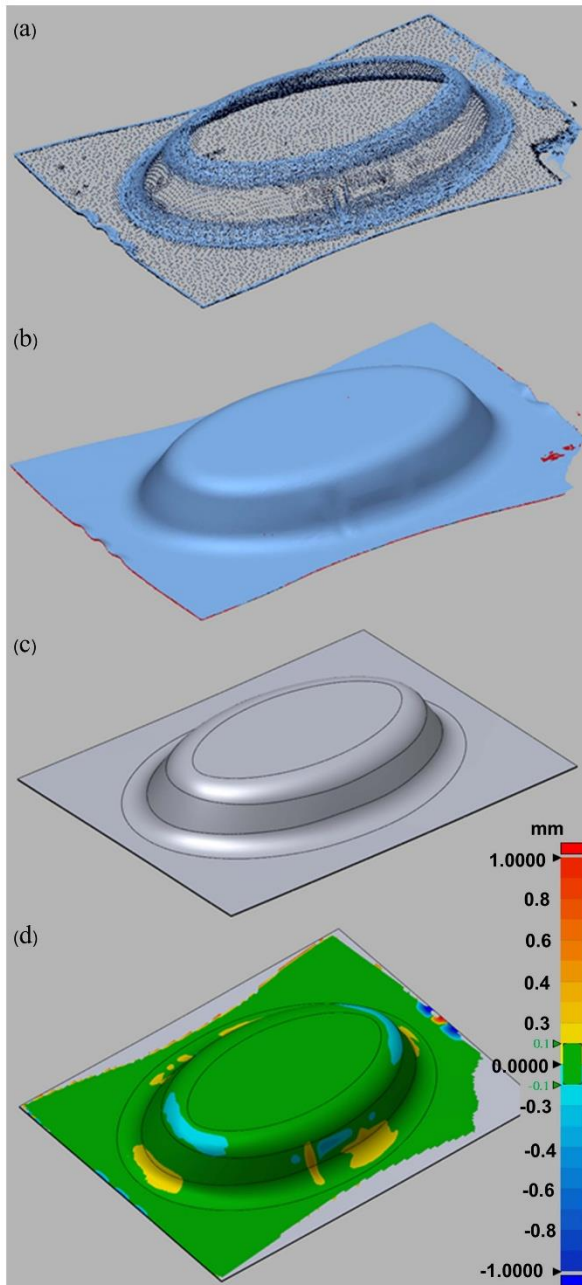


Figure 8 Reverse engineering of the cup shape.

Following the scanning and reverse engineering stages, the design and production of the deep drawing die components were executed, as illustrated in Figure 9 (a). The die components were fabricated from S50C steel as illustrated in figures 9 (b)-(i), while the components in figures 9 (j)-(m) consisted of standard parts. Figure 10. presents the assembled deep drawing die within the stamping machine and the workpiece. The initial blank, a rectangle of 304 stainless steel with a 0.5 mm thickness, 110 mm width, and 170 mm length, underwent forming. Subsequently, a cross-sectional and thickness measurement of the formed sheet metal blank are detailed in figure 11.

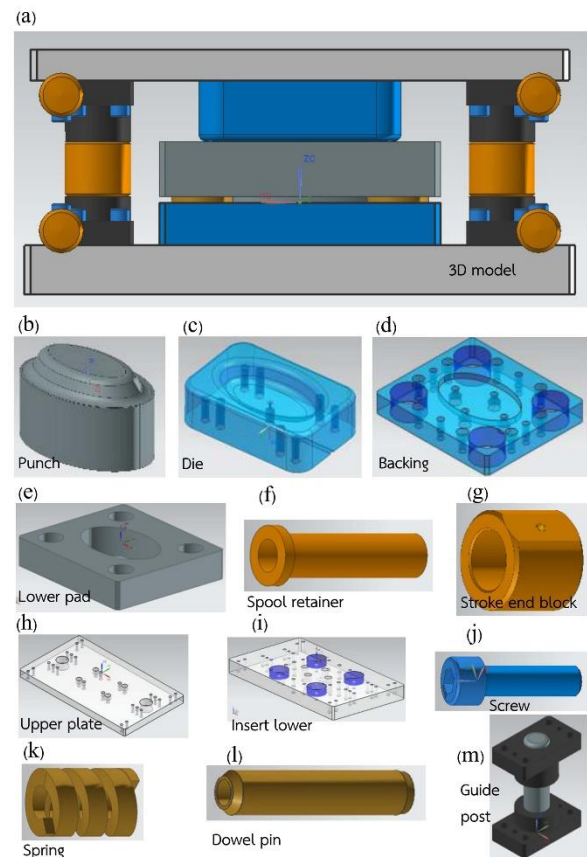


Figure 9 Deep drawing die design.

Figure 12. illustrated the thickness variations at specific locations and their relation to differing punch speeds. The integrity of the cup surface was maintained across all workpieces, with no evidence of tearing detected. However, the rim or flange (location (a)) and the bottom of the cup (location (e)) exhibited consistent thickness across varying punch speeds. The thinning phenomenon was primarily observed at locations (b)-(d), attributable to metal flow during the deep drawing process. The nose radius at location (d) exhibited the most pronounced metal flow, correlating with the area of maximum thinning. Distal to this point, the extent of thinning diminished along the cup wall (location (c)) and nose radius (location (b)). Elevated friction within the flange region promoted material migration from the nose radius and sidewall toward the periphery during forming [23].



Figure 10 Deep drawing die and workpiece.

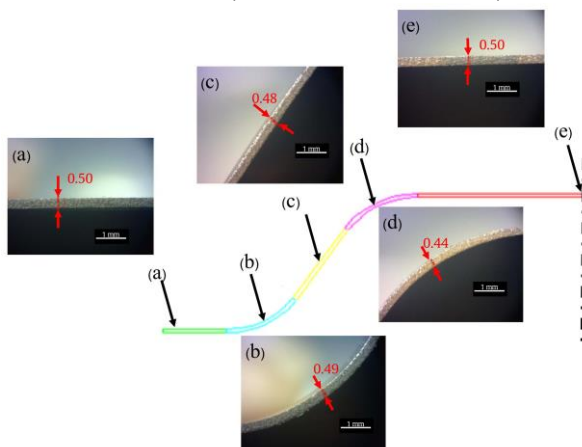


Figure 11 Thickness measurement locations on the drawn cup.

In the deep drawing process, variations in punch speed did not influence the thinning behavior observed at the flange and bottom regions of the cup. Conversely, at locations (b)-(d), an increase in the drawing speed was associated with a greater extent of maximum thinning. This can be attributed to the accelerated strain hardening of the sheet material at higher speeds, which consequently restricted its capacity for uniform deformation. This finding aligns with observations reported by Mohammed [23]. However, exceeding this drawing speed resulted in improved maximum thinning, implying that higher speeds may have promoted

enhanced metal flow and reduced localized thinning. This phenomenon was observed with a drawing speed of 1,500 mm/min, especially at location (d). Thus, the best results were obtained from the drawing speed of 1,500 mm/min according to the uniform thickness distribution and the lowest maximum thinning. Increasing the drawing speed reduced maximum thinning at location (d) where the thickness was 0.47 ± 0.0142 mm. The nose radius at location (b) with thickness was 0.48 ± 0.0141 mm. Compared to reverse engineering, the nose radius deviations were up to ± 0.20 mm. It enabled the thickness variation of the workpiece to be reduced to an acceptable range during forming.

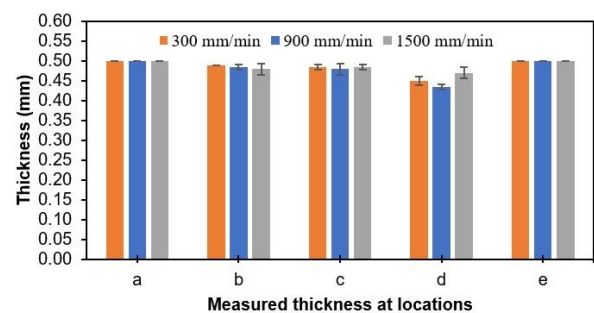


Figure 12 Relation of thickness measurement at locations and punch speed.

4. CONCLUSIONS

The research highlighted the importance of carefully selecting scanning parameters to maximize the precision and reliability of 3D scanning outcomes. The geometric characteristics of parts significantly impact the accuracy and effectiveness of 3D scanning processes. Specifically, variations in surface curvature, the presence of intricate features, and the overall complexity of the geometry significantly impacted the quality and reliability of the generated scan data. The results of scanning revealed that employing Standard details settings facilitated the creation of geometric shapes A (triangle), B (cone), C (cubic), and D (sphere). However, geometric shape E (cylinder) necessitated the use of Less details for achieving optimal scanner performance. An example of the reverse engineering of the deep drawing cup with a bank thickness of 0.5 mm using Standard details. It was found that the errors on smooth surfaces were generally within the range of ± 0.100 mm. The curved or concave edge and base of the cup exhibited an error range of approximately ± 0.200 mm.

Testing with a die created using high drawing speed indicated that the improved nose radius fell within the range of 0.47 to 0.48 $\pm$ 0.014 mm.

5. ACKNOWLEDGEMENT

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