MĀPAN-Journal of Metrology Society of India
https://doi.org/10.1007/s12647-022-00561-6

ORIGINAL PAPER

Reverse Manufacturing and 3D Inspection of Mechanical Fasteners Fabricated Using Photopolymer Jetting Technology

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Received: 18 September 2021 / Accepted: 10 April 2022

Abstract: Polyjet additive manufacturing is gaining attention owing to its ability to manufacture intricate parts with microscopic resolution. This study investigates the spatial precision of mechanical fasteners utilizing the 3D scanning technology followed by reverse engineering to obtain the accuracy of polyjet fabricated components. Numerous M8 bolts, as well as nuts, are additively manufactured to replace metal fasteners in various industrial fields such as aerospace, medical, electronics, automotive, and food packaging. M8 mild steel fastener was 3D scanned using Carl Zeiss COMET L3D2 3D scanner, and precise details of the products were gathered. Three-dimensional scanning captures a large number of surface points, resulting in a more accurate representation of the object. The gathered data were used to fabricate numerous nuts and bolts utilizing the Object 260 Connex 3 printer utilizing Vero thermoplastic polymer resins. The stability of the 3D printed specimens was investigated using Carl Zeiss COMET L3D2 3D scanner. The fabricated M8 fasteners' dimensional error is investigated in all orientations and every axes, and the respective dimensional variations are shown in detail. The high-quality production of fasteners through photopolymer jetting met all accuracy criteria and fit within the IT 06 transition fit grade.

Keywords: Reverse manufacturing; Polyjet; Photopolymer Jetting; Accuracy; M8 fasteners

1. Introduction

Additive manufacturing (AM) has become an integral aspect of manufacturing society [1]. It is one of the fastest-growing and most promising production methods, with considerable benefits over traditional fabrication methods [2]. AM enables the implementation of weight factor and design process techniques to analyze the data. As product complexity grows, AM is more dependable, requiring fewer stocks, less tooling, and minimum material waste. With the fast advancement of 3D scanning, reverse manufacturing of conventional mechanical components such as turbine blades, gears, bushes, and valves is emerging as a potential manufacturing alternative that might eventually replace conventional manufacturing [3, 4]. Three-dimensional scanners are rapidly becoming the most critical component of reverse manufacturing, playing a critical role in today's reverse engineering situation.

A variety of advancements in reverse manufacturing have been reported in the last 5 years [5–11]. Various reverse manufacturing tools have been comprehensively studied which identifies the numerous reverse engineering models. The unique combination of 3D scanning, reverse engineering, and rapid prototyping escalates the quality control for products fabricated using rubber and analyzes them for any geometric errors using the 3D SRE technique [5, 6]. Automotive products of metal sheets are extensively scanned along with the likes of re-manufacturing and compared with the data from the cloud and 3D CAD for inspection purposes [7]. An extensive study regarding the algorithmic steps required to reverse engineer the shapes along with data capturing, data calibration, data acquisition techniques is performed [8]. An intricate comparison of dimensional aspects between coordinate measuring machines (CMM) and 3D white light scanning technologies for the turbine blades is presented. CMM reports better accuracy, while the 3D scanner reports more surface capture ability [9]. Reverse engineering followed by rapid prototyping of a Ferrari 250 Mille Miglia using the optical

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3D acquisition based on the projection of incoherent light, point cloud alignment, and the triangle model definition shows that optical 3D gauging with OPL-3D over measurement holds much authenticity in case of larger volumes [10].

Nylon fasteners and plastic bolts are extensively utilized in a variety of applications [12–16]. In medical applications, polymer materials [12] such as turbine blades, gears, bushes, and valves are often used. To replace metal bolts with similar mechanical strength, orthopedic bolts were produced with the fused deposition modeling method [13]. PLA (polylactic acid) screws [14] may be used for a variety of medicinal purposes. They were used to treat several patients who had acquired syndesmosis. Due to their high-strength-to-weight ratio, fasteners [15] made from reinforcing carbon fiber and poly-ether-ether-ketone are widely used in aircraft building. A lightweight thermoplastic reinforced structure is discussed in similar research [16] that can replace metallic rivets and exhibits a higher mechanical strength.

Three-dimensional scanning technology is a non-contact inspection method, ideal for inspecting delicate parts. The benefit of a 3D scanner is in its simplicity of usage, which stems from the reduced scan times and less demanding operator's skill set. Three-dimensional scanning captures more quantity of images and surface points that statistically result in a more accurate representation of complicated geometries. Digital modeling provides a quicker and more cost-effective solution which serves as an excellent option for generating solid representations of contoured objects with high dimensional precision. These models provide a valuable source of information that may be used for the study.

2. Research Background

The applications of 3D scanning technologies demonstrate their ability for a wide variety of applications in the domain of additive manufacturing, health, automobile, and aviation where precise measurements are required [17–21]. This technology has displayed enormous potential in health care industries such as manufacturing of face masks for the health-line workers in the COVID-19 pandemic employing 3D scanning technology to assure an exact fit across the mouth, ears, and chin [17]. Widespread applications in automotive designing and testing of numerous physical parts consisting of intricate and complex geometries are displayed [18]. The laser scanning technology is utilized widely in the reverse manufacturing of heavy aircraft parts [19]. Low-cost 3D scanning devices have been developed to gather CAD data using the triangulation concept and are widely adopted for scanning the mechanical components [20, 21].

Numerous industrial components fabricated using the FDM process achieved dimensional tolerances in the International Tolerance (IT) limit of IT-09 [22, 23]. The 3D scanning technique is widely used for reverse engineering of end-use industrial products and to improve manufacturing standards for a variety of 3D printing methods. It has several uses in fields like robotics, medicine, automobiles, and electronics. Numerous research has been conducted on metal 3D printing of bolts; however, only a few studies have been implemented on reverse manufacturing for thermoplastic fasteners which lack the investigative study in the field of 3D scanning and inspection [24]. The goal of the experimental study is to develop dimensional tolerance criteria for reverse manufacturing of mechanical fasteners generated utilizing the 3D scanning technology and polyjet additive manufacturing approach followed by reverse engineering to determine the accuracy of fabricated components. This investigation also demonstrates the ability of 3D scanning technology to reproduce thermos-plastic mechanical fasteners fabricated using the polyjet AM method.

3. Methodology

In the polyjet AM process, a liquid photopolymer material is sprayed onto the printer's build platform, where it is hardened by a UV chamber to build the 3D geometry. Polyjet AM possesses the potential to control the composition, shape, and characteristics of 3D-printed objects at the microscopic level. Polyjet AM is widely used in the fabrication of precise and complex features such as hollow portions, ridges, undercuts, and canopies. Polyjet printers are capable of generating complex components in a short period, which makes them ideal for creating realistic components and prototypes. Recreating existing products using a 3D scanner has opened up new conventions for AM thermos-plastic fasteners, for low-strength joining applications and proven to be very effective, less time-consuming, and cost-cutting.

This paper puts forward the reverse manufacturing and 3D inspection of mechanical fasteners where mild steel M8 fasteners are 3D scanned under Carl Zeiss 3D scanner and fabricated using photopolymer jetting technology employing numerous Vero thermoplastic resins such as Vero gray, Vero cyan, Vero magenta, and Vero white. The dimensional performance of the fabricated M8 fasteners is examined in all orientations and along all principal axes. The stability of the printed structures was evaluated with the help of a 3D scanner, and the investigated results are analyzed in this study. The scanned geometric details are superimposed on the fastener's CAD model. The dimensional analysis is carried out at several locations on the peripheral to capture the error values. Furthermore, the dimensional performance of the AM fasteners is examined by evaluating the dimensional tolerance.

Mild steel M8 bolt and M8 nut are 3D scanned utilizing a 3D scanner. The data gathered by the scanner is processed in the software which is utilized for mesh generation, repairing, orienting the geometry of the product, and defining the mesh's location. Following 3D scanning and processing of the data acquired, the fasteners.stl file is 3D printed using a photopolymer jetting 3D printer. Figure 1 summarizes the algorithm for 3D scanning and inspection for reverse manufacturing. Various bolts and nuts were AM using the polyjet method with Vero thermoplastic resins employing various colors such as gray, white, magenta, and cyan followed by 3D scanning of M8 fasteners. Vero series photopolymer thermoplastic resins provide durability, stability, and resistance to chemicals and corrosion. Bolts and nuts are dimensionally inspected by scanning them with a high-precision 3D scanner. To conduct additional analysis, the scanned fasteners' findings are overlaid on their ISO 724-compliant CAD design. To reduce recorded data uncertainties, the dimensional deviation is evaluated at three random parts of the design. Finally, the 3D printed fasteners' behaviors are compared to verify the printer's capacity to replicate M8 fasteners.

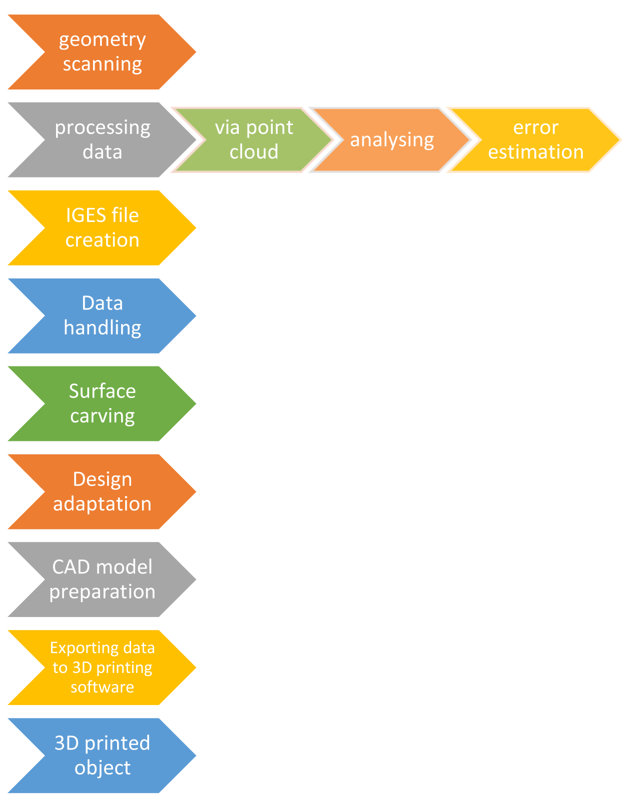

Fig. 1 Three-dimensional scanning and inspection for reverse manufacturing

3.1. M8 Bolt and Nut design

Hexagonal-headed fasteners are extensively utilized in a variety of industrial applications such as mechanical fastening. Table 1 illustrates the geometric characteristics including length of thread engagement (H), pitch, and nominal diameter depth (B). Table 2 lists the nut's geometric characteristics including the thickness of nut, height, and width of the nut.

Figure 2 depicts the M8 fasteners thread profile in accordance with ISO 724 which is utilized to develop the CAD model according to standard dimensioning data. ISO 68-1 defines the nominal dimensions of the M8 CAD model for metric threads, which describes the geometry depending on thread pitch (P) and nominal diameter (D). Figure 2c depicts the basic thread geometry, where P and H are linked by the relation.

$$H = \frac{\sqrt{3}}{2} P \quad (1)$$

The conversion of the CAD model to the stereolithographic file format is carried out by connecting the model's data through surface triangulations.

3.2. Limits and Fits

The fastener's overall functionality is dependent on the fit between the mating parts. It is based on the fundamental classes formulated based on shaft and hole designated as IT0l, IT0, and IT1 to IT16 in accordance with IS 919. The expression for the classes are defined as follows:

$$T = K \times i \quad (2)$$

where T is the tolerance (in micrometers), K is the constant, and i is the standard tolerance value (in micrometers) which is obtained by the expression:

$$i = 0.453\sqrt{D} + 0.001D \quad (3)$$

where D is defined as:

$$D = \sqrt{D1D2} \quad (4)$$

The upper limit and lower limits of nominal sizes are represented by D1 and D2 (in mm). The upper and lower limit bounds the tolerance zone of fasteners thread which has is typically confined to a narrow tolerance zone. The International Organization for Standards (ISO) defines the permissible amount of dimensional variance and its position concerning its basic size defines the tolerance zone while manufacturing a threaded fastener [26]. In accordance with ISO 965, for IT06 class, it is shown in

Table 1 Sizes of M8 bolt

Mean diameter (in mm)	M6	M8	M10	M12	M14
Length of thread engagement × Nominal diameter depth	4 × 10	5.5 × 13	7 × 17	8 × 19	9 × 22
Thread's pitch	1	1.25	1.5	1.75	2

Table 2 Sizes of M8 nut

Nominal diameter (in mm)	M6	M8	M10	M12	M14
Thickness (m)	5.2	6.5	8	10	12.8
Height (s)	11	13	17	19	20.67
Width (e)	10	15	19.6	21.9	23.36

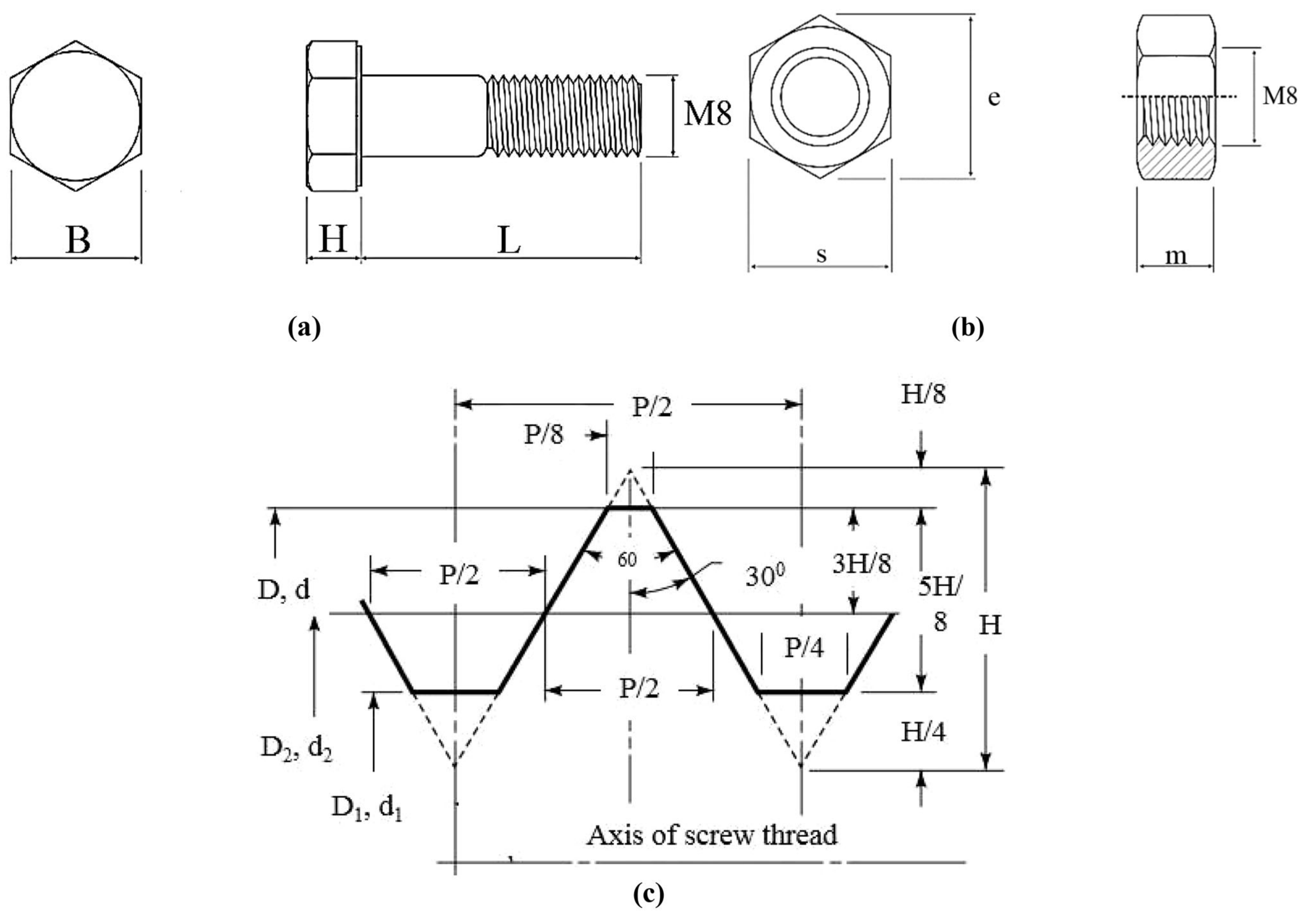

Fig. 2 **a** M8 bolt's dimensions. **b** M8 nut's dimension. **c** Thread geometry according to ISO 68-1

Fig. 3, including the standard electroplating tolerances. The mating part's fit represented as M 8*1–7 H/5 g 6 g for the threaded fastener defines a 7 H tolerance zone for the nut, nominal diameter of 8 mm, pitch of 1 mm, tolerance zone of 5 g for pitch, and 6 g for the major diameter of the thread. The accuracy of fasteners' thread profile is essential for successful mating of counterparts which affects the mechanical performance of threaded fasteners.

3.3. Three-dimensional Scanning of M8 Mild Steel Fastener

Three-dimensional scanning is a method for examining the component's fine features. The geometric characteristics of the fastener were analyzed, and the collected measurements were compared to the ISO requirements using a Carl Zeiss COMET L3D2 3D scanner [27]. The scanner has a theoretical resolution of 24 µm. Sixteen locations on the

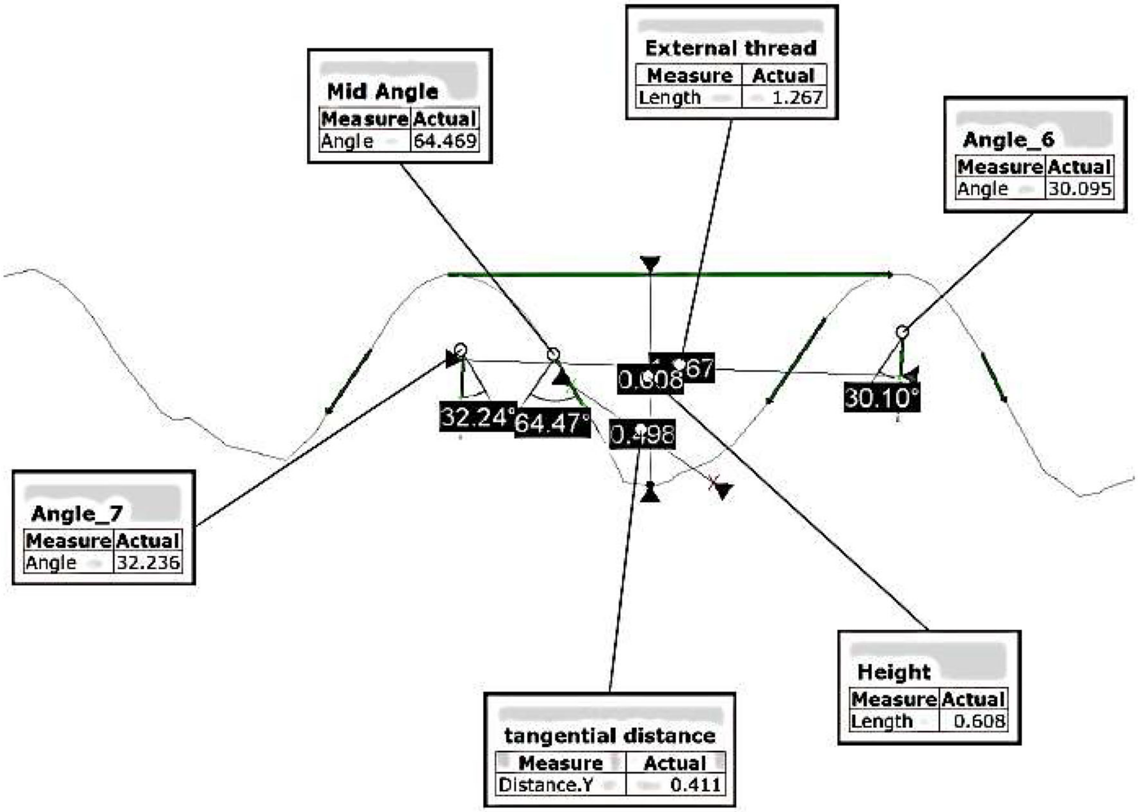

Fig. 3 Analysis of the geometric features of M8 mild steel's thread profile

geometric characteristics of the mild steel M8 bolt are examined, with the findings summed in form of dimensional variation. ZEISS colin3D software is used to collect the deviation data points along the applicate, ordinate, and abscissa, respectively. Each scan took 20 s to record a particular viewpoint, and the fasteners were scanned eight times in total to acquire the entire geometry in the auto-scan method. Before scanning, the scanner was calibrated to determine the relative positions of the camera and projector. Figure 3 shows a 4° variation in the mild steel bolt's angle of thread angle obtained using a 3D scanner.

3.4. Polyjet AM Technique

Polyjet 3D printing is a technique that includes spraying polymeric material in order of jets to create fine levels which will then be hardened to create three-dimensional objects. Polyjet AM allows the printing of polymers in a variety of materials and colors. It is often used to create intricate geometries in numerous sectors including aerospace, medical, electronics, automotive, and food packaging. Polyjet printing is highly accurate and capable of producing layers as thin as sixteen microns [28]. Polyjet printing use photopolymer materials to construct the real object and needs another gel-like substance that provides support to the structure while fabrication. Due to the dissolvable and fusible nature of the supporting materials, removing them is a straightforward and damage-free procedure. The polyjet 3D printer is shown in Figs. 4 and 5, respectively. The modeled fasteners on AutoCAD were transferred to the Connex 3 polyjet printer through their STL files. During postprocessing, a jet of water cannon is usually utilized to eliminate the SUP 705 material (support material). Numerous production concerns and parametric analysis must be considered throughout the photopolymer jetting printer manufacturing process.

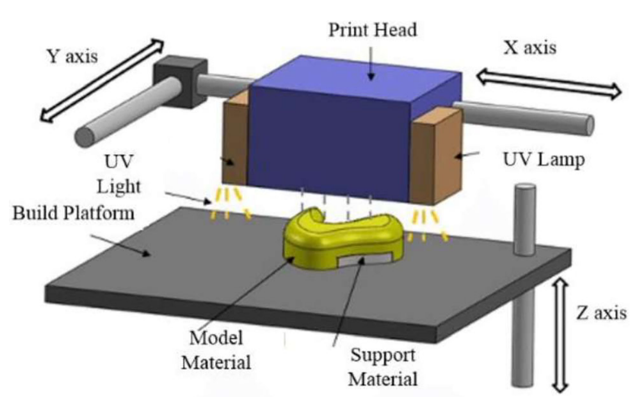

Fig. 4 Schematic of polyjet printer

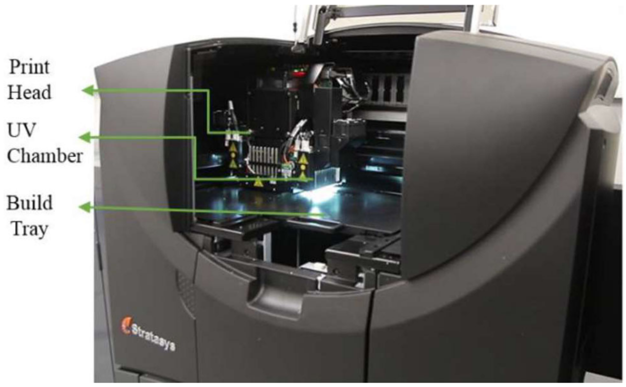

Fig. 5 Stratasys Object 260 Connex 3 polyjet 3D printer

M8 fasteners were manufactured using Connex 3 polyjet printer. The printing characteristics for polyjet fabrication comprise ultraviolet light of 1.5 kw and a wavelength of 1070 nm. Fasteners construction was accomplished in 3 h with the ambient temperature set to 25 °C. Figure 6 shows 3D-printed Vero thermoplastic bolts fabricated using white, cyan, white, magenta-colored resins, respectively. Along with a polyjet fabricated Vero thermoplastic M8 gray nut, a polyjet printed half M8 nut is also manufactured depicting internal threads to scan the interior threads while retaining the M8 nut's material and manufacturing circumstances.

3.5. Three-Dimensional Analysis Polyjet Printed Fastener

The dimensional analysis is carried out using generated by superimposing the scanned results of the polyjet printed specimen by the 3D scanner with the original CAD model in terms of dimensional deviation. Figure 7a depicts the CAD model, Fig. 7b depicts the digital model generated by the scanner, and Fig. 7c represents the alignment of the CAD model with the scanned model, respectively. The nominal value, the actual value, and the variances between the captured and ISO dimensions are compared.

Points are randomly assigned to these areas on the perimeter of the Vero thermoplastic fastener. The negative and positive value on the 3D visualization results indicates a lower dimension than the standard value and a size greater than the standard value, respectively. The analyzed points function as the reference points generated for determining the direction of departure. The directional deviations and total deviations are computed, and the dimensions are inspected along the *X*, *Y*, and *Z* axes. To determine the displacement field, the origin is positioned at the central location of the fastener, and the horizontal and vertical directions are assumed to be positive *X* and *Y* axes, respectively.

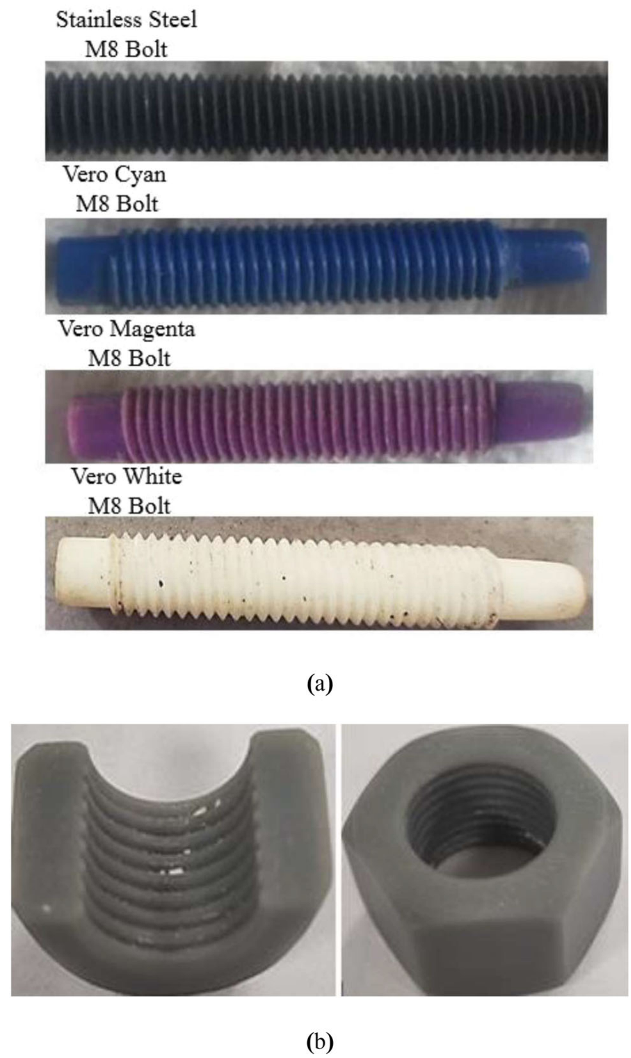

Fig. 6 Polyjet printed M8 fasteners **a** Mild steel bolt along with polyjet printed Vero thermoplastic bolts. **b** Polyjet printed M8 nut

Figures 8 and 9 represent a deviation of 4.469° and 3.278° for Vero thermoplastic fastener in Cyan and magenta-colored resin, respectively. Pitch describes the area in between two consecutive threads. The optimum deviation is observed for the radial distance measured between the crest's base, and the minimal deviation is observed for the pitch. The fastener's depth of thread is defined as the distance measured from consecutive thread bases in a plane perpendicular to the axes. While determining the depth of thread, Vero thermoplastic fabricated using cyan-colored resin reports a discrepancy of 0.176 mm for as well as 0.21 mm for Vero thermoplastic fabricated using magenta-colored resin. Figure 10 illustrates the thread characteristic of a Vero thermoplastic fastener fabricated using white-colored resin. The angle of fasteners deflects by a total of 2.5°, while the length of thread engagement deviates by a minimum of 0.8 mm.

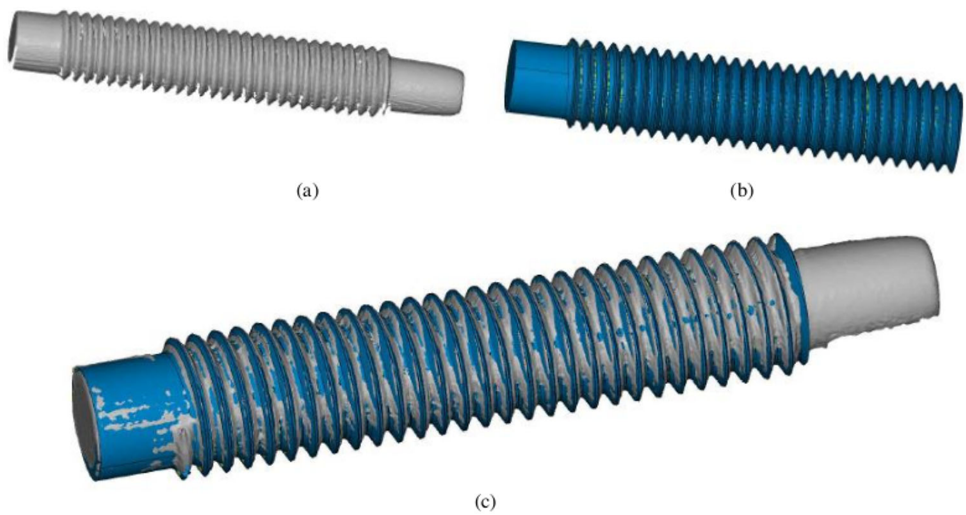

Fig. 7 Digital models of M8 fastener **a** CAD model. **b** Scanned model. **c** Alignment of CAD model with the digital model

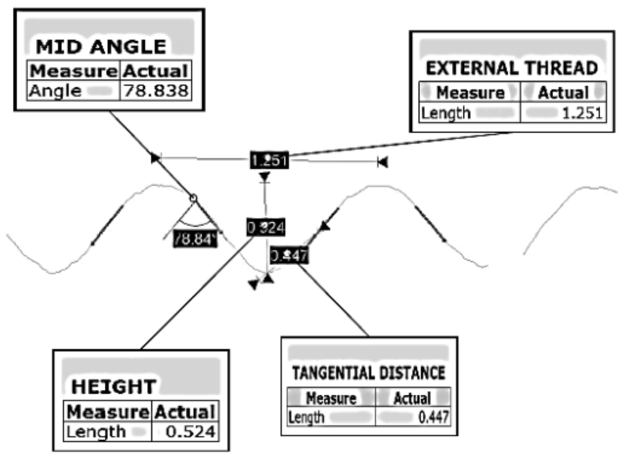

Fig. 8 Analysis of the geometric features of Vero cyan's thread profile

The chart in Fig. 11 represents the thread's dimensional tolerance. It governs the mating accuracy of the fastener. The red zone of the chart depicts the highest variation, whereas the green zone indicates the least deviation which occurs at the top surface and near threads, respectively. It can also be observed that the majority of the profile's crests and peaks are unaligned at the bottom of the fastener. Finally, Table 3 summarizes the thread profile parameters for the various Vero thermoplastic polymers. It can be seen that pitch value and thread angle deviate maximum for M8 mild steel bolt, whereas minimum for Vero cyan and Vero magenta, respectively. The thread depth's value and length of thread engagement differ majorly for Vero magenta, whereas minimum for M8 mild steel bolt and Vero cyan, respectively.

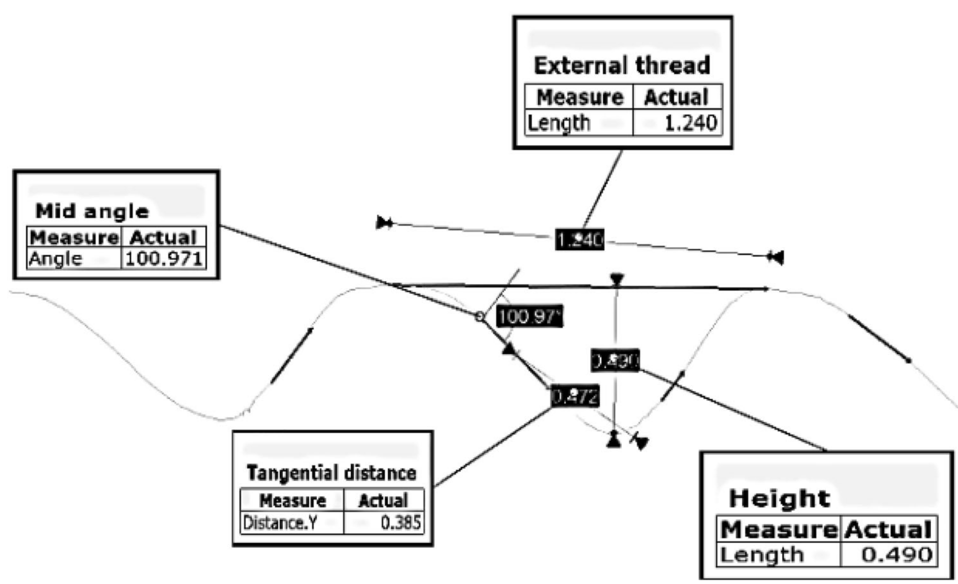

Fig. 9 Analysis of the geometric features of Vero magenta's thread profile

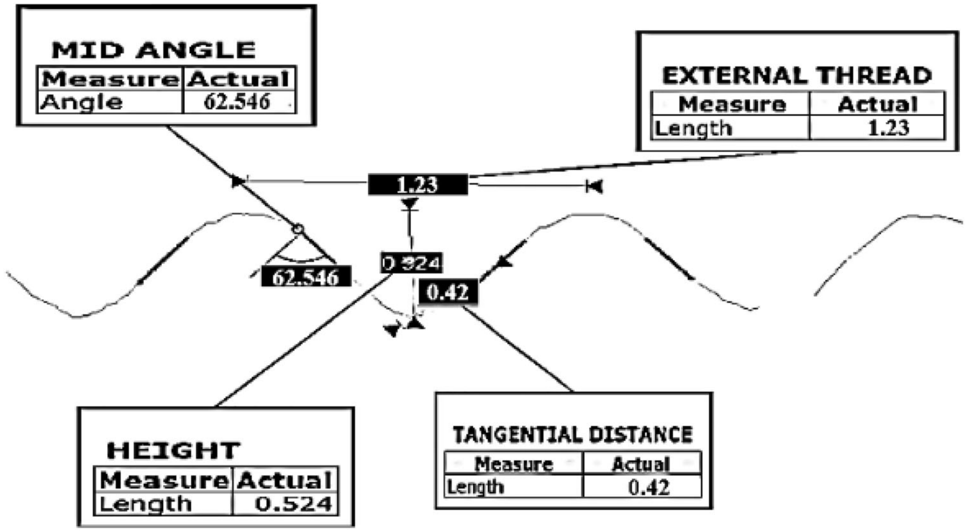

Fig. 10 Analysis of the geometric features of Vero white's thread profile

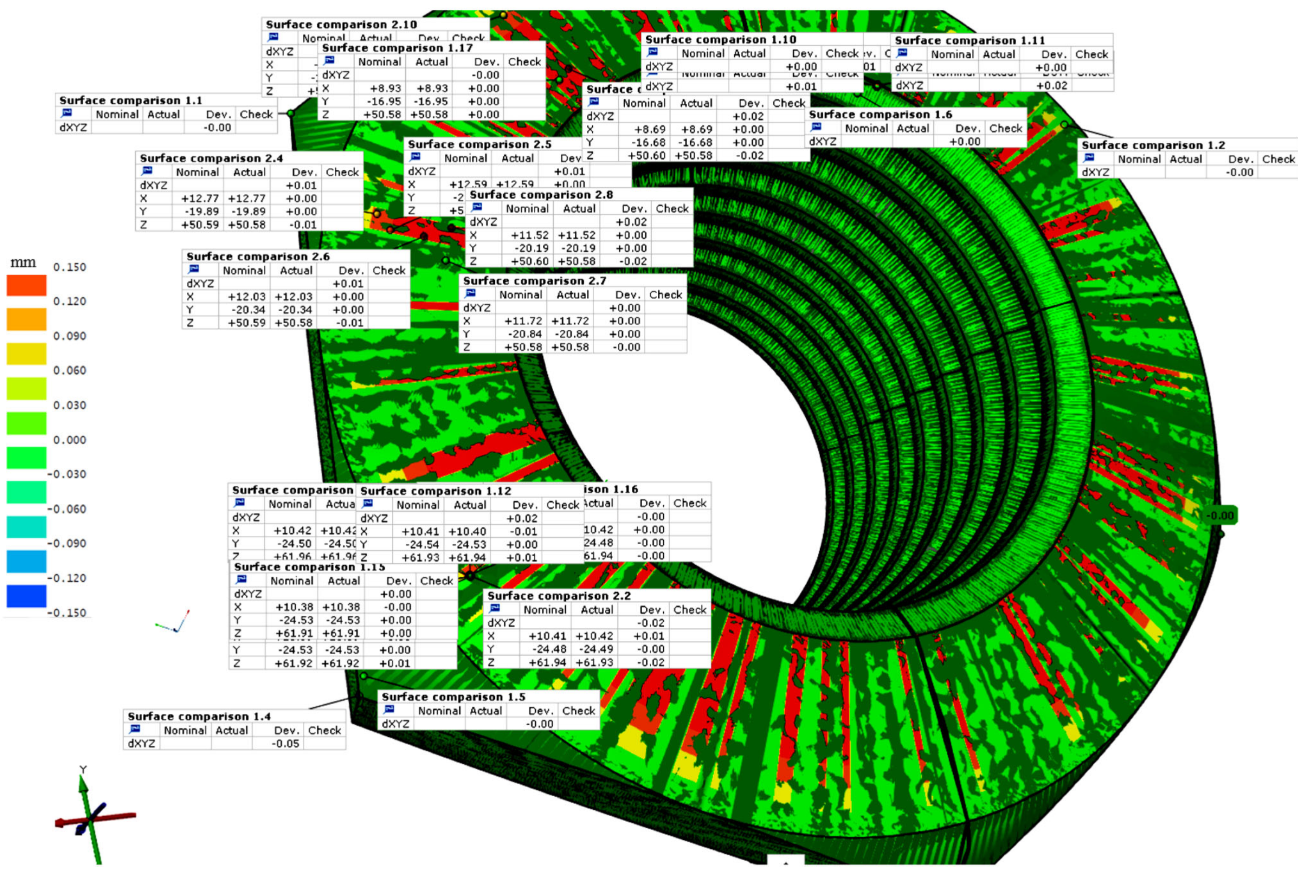

Fig. 11 Dimensional deviation illustration for Vero thermoplastic AM nut using gray-colored resin

3.6. Dimensional Deviation

The dimensional deviation is the variation thread's geometric features among the mating parts. The accuracy of the thread profile determines the successful connection between mating parts for the M8 fastener. Figure 12a-d illustrates the dimensional variation for Vero thermoplastic fastener for various colored resins including white, cyan, magenta, and gray, respectively. It is noticed that the values are higher alongside ordinate for cyan-colored

Table 3 Thread profile parameters for the various Vero thermoplastic polymers

Parameters	Pitch (P), mm	Thread angle, degree	Thread's depth (B), mm	Length of thread engagement (H), mm
Standard values	1.25	60	0.7	0.5
M8 mild steel bolt	1.267	64.469	0.608	0.411
Vero Cyan	1.251	63.278	0.524	0.447
Vero Magenta	1.24	63.898	0.49	0.385

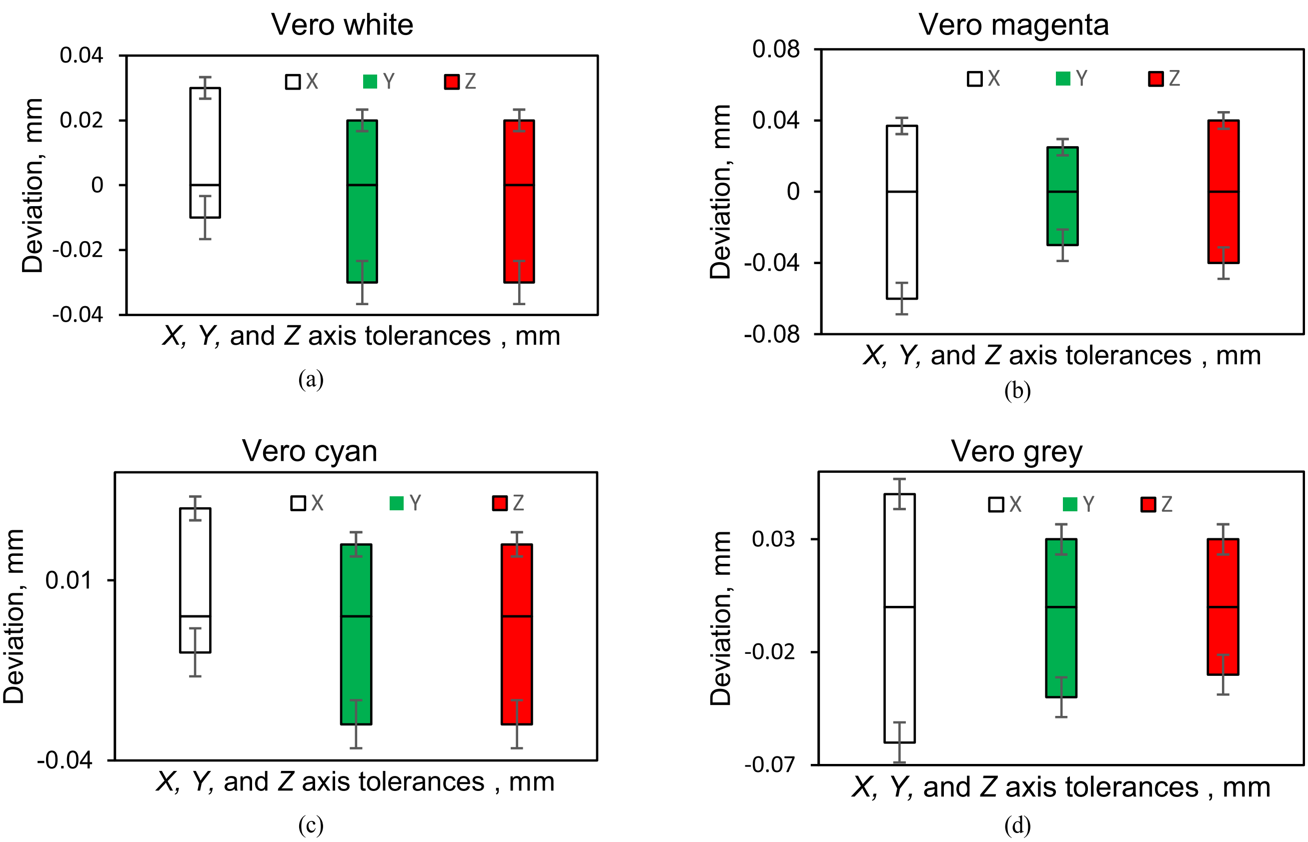

Fig. 12 Mean dimensional tolerances for the M8 fasteners fabricated using **a** Vero white, **b** Vero magenta, **c** Vero cyan, **d** Vero gray thermoplastics

thermoplastic resin, greater alongside the applicate for Vero white and magenta-colored thermoplastic resin. The optimum deviation is observed at the fastener's top surface and minimal at the base of the fastener. The maximum crests and peaks are unaligned at missed at the bottom region of the fastener. For thermoplastic fastener fabricated using gray-colored resin, the dimensional error is the highest along the ordinate. The mean dimensional deviation for cyan-colored, magenta-colored, and white-colored Vero thermoplastic fasteners are ± 0.09 ± 0.12 mm and ± 0.14 mm, respectively. For the gray-colored Vero thermoplastic fastener, the extreme variation is ± 0.1 mm.

4. Conclusion

The reverse manufacturing for thermoplastic M8 fasteners using photopolymer jetting technology was demonstrated to facilitate the introduction of thermoplastic fasteners particularly suited for low-strength joining applications. A 3D scanner was used to evaluate the dimensional performance of an M8 mild steel fastener. M8 thermoplastic fasteners were printed using polyjet AM utilizing the data collected from a 3D scanner. Vero thermoplastic fasteners are fabricated using resins of numerous colors including cyan, magenta, white, and gray using photopolymer jetting technology. Vero thermoplastics are lightweight and show a broad spectrum of critical thermal–mechanical characteristics, including hardness, brittleness, and toughness. The 3D scanning observations for Vero thermoplastic's scanned samples were analyzed and compared. After evaluating the mating components' geometric features, it was found that pitch value deviation was least, while the thread depth error was found to be the most for the Vero magenta bolt. The internal threading of the mating nut fits precisely with the Vero thermoplastic bolt's peaks and valleys. Vero series thermoplastics produced M8 fasteners with an overall variation of 0.12 mm. Polyjet technology has the potential to fabricate fasteners using similar fabrication conditions. Overall, it could be established that the successful thread connections between M8 bolts and M8 nuts produced by Polyjet AM are feasible in the IT 06 transition fit and have a maximum variation of less than 6 g tolerance band. Thus, photopolymer jetting as a technique may be very advantageous as it does not require any scaling factor in the manufacture of the majority of designs before manufacturing. The study may assist experts and software developers in developing a variety of AM models and relationships. This approach may save a lot of time and money since conventional measuring techniques like calipers, rulers, and so on need time and expertise.

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