Case Study

Comparison of similar injection moulded parts by a coordinate measuring machine

Samir Lemes¹

© Springer Nature Switzerland AG 2019

Abstract

One of the biggest issues in measuring injection moulded parts by touch-probe coordinate measuring machine is the deformation of parts being measured. Even though the contact force rarely exceeds 200 mN, it can deform the part, or influence the fixture, thus introducing measurement error. In order to provide the most appropriate measurement method for the inspection of injection moulded part geometry, this paper combines two research topics: one is the comparison of measurement objects similar in shape—expensive brand name products with cheap no-name products, and another is the deformation analysis of the contact between the CMM touch-probe and flexible polymer parts which tend to deform when this type of measurement is used.

Keywords Coordinate measuring machine · Product quality · Injection moulded parts

JEL Classification L15 · L16 · C63

Mathematics Subject Classification 28A75 · 74S05

1 Introduction

Coordinate measuring machines (CMM's) are widely accepted for highly precise control of manufactured parts' geometry. Compared with traditional measurement techniques (as shown in Fig. 1), they have high accuracy, high repeatability and can easily be automated. The accuracy of measurements shown in Fig. 1 largely depend on the measurement technique, i.e. the contact force between the measuring device and the measurand varies.

In order to estimate the relation between the production costs and the geometrical tolerances, a number of researches were performed. Some of the analysed the manufacturing aspects, some investigated the material properties, and some were focused on reverse engineering technologies in order to test the geometry of manufactured parts [1]. Ebro and Howard in [2] investigated variation reduction principles (VRP) that can be used to

increase the robustness of a product and reduce its variation in functional performance. Singh and Bettig in [3] evaluated and compared different schemes for capturing the attributes of assembly interfaces and appending that information to solid CAD models. Bici et al. in [4] used Reverse Engineering and Computer Aided technologies to improve the inspection of injection moulded electro-mechanical parts. They used a laser scanner installed on a CMM machine in order to measure components with lengths in the range of 5÷250 mm, and special issue they had to deal with were the measurement algorithms for cylindrical features, in order to have the same level of reliability obtained in the planar case. Bici et al. in [5] used Computer Aided Tolerancing and Inspection (CAT&I) methods based on Reverse Engineering techniques to test an aeronautical component made by beta-forging of Ti6Al4V Titanium Alloy powders in order to test the implementation oriented to non-planar surface recognition. Bici et al.

✉ Samir Lemes, slemes@unze.ba | ¹University of Zenica, Fakultetska 1, 72000 Zenica, Bosnia and Herzegovina.

Fig. 1 Some traditional measuring instruments for geometric dimensioning and tolerancing

in [6] compared the laser scanning with CMM, presenting a method that could overcome the bottlenecks of non-contact measurements for planar [6] and cylindrical [7] geometry. Busick et al. in [8] propose a methodology for using process simulation in evaluating the feasibility of a tolerance scheme, describing the steps required for estimating the dimensional errors and defining criticality as a measure of tolerance feasibility. Turc et al. in [9] presented a methodology to estimate the mould cost, taking into consideration the part geometry and its dimensional prescriptions.

Gasparin et al. in [10] used optical CMM to perform the inspection of injection-moulded micro parts. The parts had dimensions between 0.19 and 9.00 mm, and the maximum permissible error (MPE) of the measuring machine was 4.0 μm . They raised an issue of part deformation, since small products made of plastics could be deformed when measured by contact CMM's. However, optical measurements had different difficulties, such as finding the edge, contrast between the dark and light areas, and fixing the parts for measurements. Kovács and Sikló in [11] discussed the warpage of injection moulded parts due to technological process parameters. They stated that dimensional errors in these parts largely depend on the manufacturing process. This could lead to conclusion that it is not enough to have tools made with high precision, but also material properties and other manufacturing parameters should be kept within strict control in order to obtain high quality products. Ontiveros et al. in [12] used computed tomography (CT) for parts inspection to overcome disadvantages of touch-probe and optical measurements. CT can provide the insight into internal dimensions of the parts,

avoiding the deformation of polymer parts due to contact with touch-probe, and allowing all dimensions to be controlled and kept within prescribed tolerances.

Varady et al. in [13] addressed the characterization of geometric models and related surface representations, segmentation and surface fitting for simple and free-form shapes, multiple view combination and creating consistent and accurate B-rep models. They mentioned the small draft angles as a necessary feature in moulds, which should be taken in account during the optical or contact measurements. Raja and Fernandes in [14] thoroughly discussed all aspects of reverse engineering, from rapid prototyping to legal aspects. The purpose of this research was not to perform the reverse engineering of expensive toybricks, but to estimate the quality and dimensional tolerances of these products. A vast literature review about geometrical and dimensional tolerancing in reverse engineering was performed by Kaisarlis in [15]. The same reference shows a number of valuable recommendations on how to determine the dimension tolerances when there is not enough technical data available.

However, in addition to real product quality, the price of the final product largely depends on market status and implementation of copyright protection. In other words, the brand name sells the product, and [1] have shown that the key factor for market price of injection moulded toy bricks is not only branding and copyright, but also the real product quality. The product quality in this research was observed through dimension and shape tolerances of toy bricks manufactured by the famous LEGO® company and by no-name imitation made in China.

2 Description of products being tested

In addition to the real manufacturing and distribution costs, the product price is primarily determined based on its market position. It is not uncommon to have anonymous producers trying to imitate the famous brands in order to find a way to their customers. Figure 2 shows some examples of popular brands imitated by their counterfeits.

LEGO® is famous Danish creator and manufacturer of children's toys. In the beginning, LEGO® produced only wooden toys, but for the past 40 years, their major product is based on injection-moulded toy bricks. The toy bricks can simply be merged and separated, which contributes to the assembly speed. The first LEGO® toy bricks were made in 1949, when the company's management made the decision to invest in the development of injection moulding equipment and began research related to the production of toys [16].

The LEGO® toy bricks material is Acrylonitrile/Butadiene/Styrene (ABS). It is a polymer material that belongs to the group of plastomers and is characterized by good mechanical properties: considerable strength, hardness and rigidity, good dimensional stability, good abrasion resistance, UV-sensitivity [17]. The nominal dimensions are integer numbers, when measured in millimetres.

There are no official data publicly available about tolerances of LEGO® toy bricks. The usual deviations from the nominal dimensions of injection-moulded products range between 0.01 and 0.1 mm. Moulds for plastic injection are subject to strict dimensional controls. Internal/external length, width and height, and geometric characteristics such as parallelism, flatness, etc. are usually examined. Plastic injection moulding tolerances range from 0.005 to 0.05 mm [18].

Counterfeit toy bricks are usually made of Plastified polyvinyl chloride (PVC-P). Both ABS and PVC-P

are thermoplastics, but their properties, as presented in Table 1, differ significantly.

3 Measurement of nominal linear dimensions

There main dimensions of LEGO® toy bricks are presented in Fig. 3. The measurement of dimensions was performed by the coordinate measuring machine "ZEISS CONTURA G2" (Fig. 4). The measurement uncertainty of this machine is $\pm 1.8 \mu\text{m}$.

Although no-name bricks are similar in shape to LEGO® bricks, they differ in a way that there is no central cylinder. Both products do have ribbed reinforcements placed on each side of the brick. These brick elements ensure the proper functioning of the brick because the small cylinders of the adjoining bricks located on the upper outer surface are fitted in the cavities between the ribbed reinforcements and the central cylinder of the brick. These elements contact each other and ensure proper and good fitting of the bricks. The ribbed reinforcements serve, in addition to contacting another brick, to increase the rigidity and strength of the brick, and to avoid the appearance of cavities, strains and stress concentrations during injection moulding [1].

The reinforcements in the inside of the brick walls were measured by the CMM using the measurement strategy as shown in Fig. 5.

Table 1 Properties of materials used in products being tested [19]

Property	ABS	PVC-P
Young's modulus (GPa)	2.0–2.6	1.4
Tensile strength (GPa)	37–110	16
Thermal expansion, ($\mu\text{m}/\text{m}\cdot\text{K}$)	81–95	160
Density, (g/cm^3)	1.0–1.4	1.4

Fig. 2 Examples of counterfeit consumer goods

Fig. 3 Basic dimensions of LEGO® toy bricks [20]

Fig. 4 Coordinate measuring machine "ZEISS CONTURA G2"

Fig. 5 Measurement of internal reinforcements [1]. **a** LEGO® **b** no-name counterfeit **c** measurement strategy **d** nominal dimension

Nominal dimension is the distance between the reinforcement ribs and it is 12.8 mm. Two sets of 10 products were measured, the measurement results were processed and the deviations of the nominal 12.8 mm are presented in Fig. 6. The scattering of results, calculated as the standard deviation of measured dimensions, is much smaller at LEGO® bricks. Also, the deviations from the nominal dimensions are far smaller in LEGO® bricks and their values range, on average, 32 μm for X and 41 μm for Y coordinates, whereas these values are much larger in bricks made by unknown producer and they are 160 μm for X, and 124 μm for Y coordinate. Not only that real dimensions are much more stable in LEGO® bricks, but also their scattering is significantly smaller. That means that the production process is much more stable, the dimensions do not vary much in different axes, and the high price of such products is obviously justified.

4 Measurement of circularity

Apart from the deviations of nominal dimensions, another feature was also inspected to test the product quality. Zeiss Calypso software has the capability of calculating the form tolerances, such as straightness, flatness, circularity, cylindricity, perpendicularity, parallelism, etc. The measurement of these features is standardized.

The ISO definition of circularity or roundness is based on the ratio between the inscribed and the circumscribed circles that are sufficient to fit inside and to enclose the given shape. Roundness is defined in [21] and [22] as the separation of two concentric circles that just enclose the circular section of interest. The roundness is measured by the CMM in a way that the probe is brought into contact with the component being measured and its position is recorded. A significant number

of points are taken around the component and these are then combined in accompanying software to calculate the roundness of the component. The roundness is numerically expressed as a width of tolerance zone, limited in the measuring plane, which is perpendicular to the axis, defined as the difference in radii of two concentric circles. The choice of the algorithm for roundness measurement is limited by the CMM software, which offers the standard and widely used least squares circle fitting procedure. As Kasa concluded in [23], the accuracy of roundness measurement can be improved by increasing the number of data points, which was taken into account in determining the measuring strategy on CMM. Each set of points was acquired by registering approximately 1.000 points per circle.

Figure 7 shows how the simultaneous measurement of two similar products was performed to determine the roundness of cylindrical features. Since the height of these features is only 1.8 mm, it is not possible to measure the cylindricity, and only roundness was measured.

Similar to measurements of linear dimensions, the results of roundness measurement were accordingly different for LEGO® and no-name bricks. The results shown in Fig. 8. reveal the difference between the two sets of products in ratio of 2; average roundness of LEGO® bricks is 8 μm , and the roundness of no-name bricks is 19 μm . The scattering (standard deviation) of roundness of LEGO® bricks is 4 μm , and the scattering (standard deviation) of roundness of no-name bricks is 12 μm .

Fig. 6 Deviations from nominal dimensions of LEGO® and no-name bricks 2 × 2

Fig. 7 Measuring circularity of two similar products

Fig. 8 Roundness of LEGO® and no-name bricks

5 Finite element analysis of the contact between the touch probe and polymer product

In order to check the influence of touch-probe force to measurement results, because of the flexibility of injection-moulded products tested, a finite element analysis was performed by means of the CAE software SolidWorks 2018. A 3D CAD model of a product was made, appropriate force (200 mN) was applied and the deformation was calculated as a linear static problem.

A static force was applied on a circular surface section, since SolidWorks Simulation cannot perform the analysis if the force acts in a single point. This is well-known issue in SolidWorks, which is usually resolved by making a split line or similar virtual geometry to develop a vertex to apply the force to. Sometimes soft “bushings” are used and a load is applied to it that is then transferred with a

contact condition. In this case, a small circular extrusion was created near the top of the edge, and the contact force (200 mN) was applied to the circular surface. The circle was 0.1 mm in diameter, thus simulating the contact between the stylus ball and the surface of a toybrick.

The toybrick was fully restrained at the bottom surface, as a fixed connection between the toybrick and the foundation. There could be some deviations occurring due to the contact between two toybricks, but the contact is obviously so firm that it can be taken as a fixed connection.

The materials used for simulation are ABS (Young's modulus 2.0 GPa, Poisson's Ratio 0.394 and mass density 1020 kg/m³). PVC-P (Young's modulus 2.4 GPa, Poisson's Ratio 0.383 and mass density 1300 kg/m³), and PET (Young's modulus 3.0 GPa, Poisson's Ratio 0.370 and mass density 1420 kg/m³).

Fig. 9 Finite element simulation of CMM measurement

The simulation results shown in Fig. 9 reveal that the maximum deformation of bricks made of ABS and PVC–P is $4.61\text{ }\mu\text{m}$, and the maximum deformation of brick made of PET is $3.75\text{ }\mu\text{m}$.

When compared to deviations of nominal dimensions (shown in Fig. 6), the simulation introduces significant error into the result, due to high elasticity of the material used. The average length deviation is between 20 and $100\text{ }\mu\text{m}$, and the part is deformed up to $5\text{ }\mu\text{m}$ due to contact force of the touch-probe. The significant part of deviation (5–25%) actually occurs due to the measurement process, but the difference between the materials does not contribute to overall differences in measurements, confirming that the previous results are accurate and relevant enough.

6 Conclusion

The more expensive products are usually of better quality, due to the fact that more expensive and better-quality raw materials are used for the production of more expensive products, the production technology, labour force, more expensive machinery and production processes, better quality control, etc. are used. These statements are in general, for the vast majority of cases, but there are always exceptions.

The aim of this paper was to analyse and to determine the justification of significantly higher prices of LEGO® bricks on the market compared to other manufacturers. The results of the both length and circularity measurements showed that deviations from all measured values in cheaper toy bricks were approximately 2–3 times higher compared to LEGO® bricks. When the identical dimensions for each brick were measured, it was found that cheaper products had large differences in the obtained results, while in the case of LEGO® bricks these differences were insignificant.

In addition to visible differences (finishing quality, colour stability), also the cheaper bricks expressed the poorer fitting characteristics. This was confirmed by the results of the measurements carried out, which showed that the deviations from the nominal dimensions of LEGO bricks are very small and are within the range of prescribed tolerances. In this term, it can be said that LEGO® has reasonably high price in the market and that, in terms of precision and quality control, they are unlikely to be competed in the production of injection-moulding toy bricks.

The Finite element analysis of the contact between the touch probe and polymer product showed that this contact introduces significant error into measurement results, but there was almost no difference between the material used. One can conclude that material properties do not cause the difference in results, but the real deformation is significant and it should be taken care of when flexible products are being measured on coordinate measuring machine.

This research should be followed by further tests and simulations with wider scope, taking into account the stress and strain conditions during usage, possible plastic deformations, wear of injection moulded parts, toybricks finishing and surface quality, friction between the CMM touch-probe and the part surface, temperature induced deformation, etc. Another aspect to be reconsidered is to perform the FEA analysis with contact simulation.

Compliance with ethical standards

Conflict of interest The author declares that there is no conflict of interest.

References

1. Lemeš S, Baručija A (2018) Dimension measurement of injection moulded toybricks. In: Editors: Karabegović I, Haznadar Z, Pašić S (eds) 4th International conference “new technologies NT-2018”

- development and application, 28 June 2018, Sarajevo, Bosnia and Herzegovina; Lecture notes in networks and systems, vol 42. Springer, Cham, pp 57–64. ISBN 978-3-319-90892-2. https://doi.org/10.1007/978-3-319-90893-9_6
2. Ebro M, Howard TJ (2016) Robust design principles for reducing variation in functional performance. *J Eng Des* 27(1–3):75–92. <https://doi.org/10.1080/09544828.2015.1103844>
 3. Singh P, Bettig B (2003) Port-compatibility and connectability based assembly design. In: ASME 2003 international design engineering technical conferences and computers and information in engineering conference, vol 2: 29th Design automation conference, parts A and B, Chicago, Illinois, USA, 2–6 September 2003, pp 775–784. <https://doi.org/10.1115/DETC2003/DAC-48783>
 4. Bici M, Broggiato GB, Campana F, Dughiero A (2017) Computer aided inspection procedures to support smart manufacturing of injection moulded components. *Procedia Manuf* 11:1184–1192. <https://doi.org/10.1016/j.promfg.2017.07.243>
 5. Bici M, Campana F, Testani C, Trifirò A (2014) Development of automatic tolerance inspection through reverse engineering. In: 2014 IEEE international workshop on Metrology for Aerospace, Benevento Italy. <https://doi.org/10.1109/MetroAeroSpace.2014.6865903>
 6. Bici M, Campana F, Petriaggi S, Tito L (2014) Study of a point cloud segmentation with part type recognition for tolerance inspection of plastic components via reverse engineering. *Comput Aided Des Appl* 11(6):640–648. <https://doi.org/10.1080/16864360.2014.914382>
 7. Bici M, Campana F, Trifirò A (2016) Automatic postprocessing for tolerance inspection of digitized parts made by injection moulding. *Comput Aided Des Appl*. <https://doi.org/10.1080/16864360.2016.1168231>
 8. Busick DR, Beiter KA, Ishii K (1994): Design for injection molding: Using process simulation to assess tolerance feasibility. In: Computers in engineering, proceedings ASME computers in engineering (CIE'94), vol 1, pp 113–120
 9. Turc CG, Carausu C, Belgiu G (2017) Cost analysis in injection moulded plastic parts designing. In: 2017 IOP conference series: materials science engineering, vol 227, no 1, pp 012132. <https://doi.org/10.1088/1757-899X/227/1/012132>
 10. Gasparin S, Tosello G, Hansen HN, Islam A (2013) Quality control and process capability assessment for injection-moulded micro mechanical parts. *Int J Adv Manuf Technol* 66:1295–1303. <https://doi.org/10.1007/s00170-012-4407-6>
 11. Kovács JG, Sikló B (2011) Investigation of cooling effect at corners in injection molding. *Int Commun Heat Mass Transf* 38:1330–1334. <https://doi.org/10.1016/j.icheatmasstransfer.2011.08.007>
 12. Ontiveros S et al (2012) Dimensional measurement of micro-moulded parts by computed tomography. *Meas Sci Technol* 23:125401. <https://doi.org/10.1088/0957-0233/23/12/125401>
 13. Varady T, Martin RR, Cox J (1997) Reverse engineering of geometric models—an introduction. *Comput Aided Des* 29(4):255–268. [https://doi.org/10.1016/S0010-4485\(96\)00054-1](https://doi.org/10.1016/S0010-4485(96)00054-1)
 14. Raja V, Fernandes KJ (2008) Reverse engineering: an industrial perspective, vol 18. Springer Series in Advanced Manufacturing. Springer, London. <https://doi.org/10.1007/978-1-84628-856-2>
 15. Kaisarlis GJ (2012) A systematic approach for geometrical and dimensional tolerancing in reverse engineering. InTech, In Reverse Engineering-Recent Advances and Applications. <https://doi.org/10.5772/32001>
 16. Mimoso JM (2009) A timeline of early LEGO® development. <https://www.inverso.pt/legos/Textos/timeline.htm>. Accessed 21 Jan 2018
 17. Šercer M, Križan B, Basan R (2009) Konstruisanje polimernih proizvoda. Sveučilište u Zagrebu, Zagreb
 18. Angel JAB, De Chiffre L (2013) Inter laboratory comparison on industrial computed tomography: CIA-CT comparison, final report 01, DTU mechanical engineering. http://orbit.dtu.dk/files/58959939/CIA_CT_Final_Report_01.pdf. Accessed 21 Jan 2018
 19. ABS vs. PVC-P. <https://www.makeitfrom.com/compare/Acrylonitrile-Butadiene-Styrene-ABS/Plasticized-Flexible-Polyvinyl-Chloride-PVC-P>. Accessed 21 Jan 2018
 20. Cailliau R. <https://www.cailliau.org/Lego/Dimensions/zMeasurements-en.xhtml>. Accessed 21 Jan 2018
 21. ISO 1101 Geometrical product specifications (GPS) -- Geometrical tolerancing -- Tolerances of form, orientation, location and run-out (ISO 1101:2017). International Organization for Standardization/TC 213 Dimensional and geometrical product specifications and verification (2017)
 22. ISO 12181-1 Geometrical product specifications (GPS) -- Roundness -- Part 1: vocabulary and parameters of roundness (ISO 12181-1:2011). International Organization for Standardization/TC 213 Dimensional and geometrical product specifications and verification (2011)
 23. Kasa I (1976) A circle fitting procedure and its error analysis. *IEEE Trans Instrum Meas* 25(1):8–14. <https://doi.org/10.1109/TIM.1976.6312298>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.