Journal of Machine Engineering, Vol. 17, No. 2, 2017

Received: *19 December 2016* / Accepted: *27 February 2017* / Published online: *12 June 2017*

geometrical product specifications,
part alignment,
datum

Yiqing YAN[1*]
Martin BOHN[1]

LIMITATIONS OF NOTATION SYSTEM IN CENTRED PART ALIGNMENT ACCURACY IMPOSED BY ISO STANDARD AND PROPOSAL FOR AN IMPROVED METHODOLOGY

According to the ISO Geometrical Product Specifications (GPS), centred part alignment with one centred point can be described clearly using technical drawings. There are two main limitations of this standard; Firstly: the uncertainty over use of notations in technical drawings when more than one centred point is applied, and secondly, the use of fixed datum targets to centred points which causes an unstable alignment process. This article suggests a new approach for a functional, explicitly defined notation system of datums and datum systems based on the research of orientation constraints between datums. This new approach simplifies the technical drawing, thereby eliminating notation uncertainties. An improved methodology for a stable alignment process was developed based on physical analysis of the centred part alignment which implements movable datum targets.

1. INTRODUCTION

ISO 5459:2011 [1] is the international GPS [2] standard for establishment of datums and datum systems of geometrical components in design and manufacturing, as well as standardisation of these notations in technical drawings. In ISO 5459:2011 the centred part alignment is defined by aligning a part with the derived geometrical element [3] which is a centred (or middle) plane, centred (or middle) line or centred (or middle) point. It is difficult to describe all the datums and datum systems for every variable component by using the notations imposed by ISO. This paper focuses on the notations of the datums and datum systems by centred part alignment with more than one centred point in the technical drawings. The terminology “centred point” which is used in this paper indicates the middle point which is generated after the centring process of two points from different planes. The research is based on the rules of orientation constraints of datums and through analysis of the physical behaviour of centred part alignment with centred points.

Previous works [4-14] concentrated more on the process of mathematical establishment and practical application of datums and datum systems, rather than

[1] Daimler AG, Research & Development Body in White, Dimensioning & Tolerancing, Germany
[*] E-mail: yiqing.yan@daimler.com

the notation of these within technical drawings. Moreover, the previous works have not particularly determined the limitations and deficits of using fixed datum targets by centred part alignment with centred points.

This paper proposes a function-oriented [15] reproducible and reliable notation system of datums and datum systems and offers a correspondingly improved alignment methodology using movable datum targets for the centred part alignment with centred points. This paper is constructed as follows: the state of the art including basic theory and terminologies of datums and datum systems for geometrical parts from the current ISO standards are given in section 2. The corresponding deficits of ISO are detailed and analysed by using three hierarchical components in section 3. A new approach and an improved methodology are described in section 4. The conclusion is given in section 5.

2. STATE OF THE ART

2.1. TERMINOLOGY

In order to understand the research and purpose of this paper the following important terminologies are explicated with the definitions and the illustrations:

- *Datum feature: real integral feature used for establishing a datum* [1].
- *Datum feature indicator: single features to be used for establishing datum features shall be indicated* [1]. The symbol is shown in Fig. 1.

Fig. 1. Datum feature indicator: a box linked to a filled or open datum triangle by a leader line [1]

- *Datum: is a theoretically exact reference; It is defined by a plane, a straight line or a point, or a combination thereof* [1].
- *Datum target: portion of a datum feature which can nominally be a point, a line segment or an area* [1]. The symbol is shown in Fig. 2a.
- *Moveable datum target: datum target with a controlled motion* [1]. The symbol is shown in Fig. 2b.

Fig. 2. a) fixed datum target, b) moveable datum target [1]

- *Common datum: datum established from two or more datum features considered simultaneously* [1]. Fig. 3 is an example from ISO which illustrates the establishment of common datum A-B. A-B is the centred plane of datum features A and B.

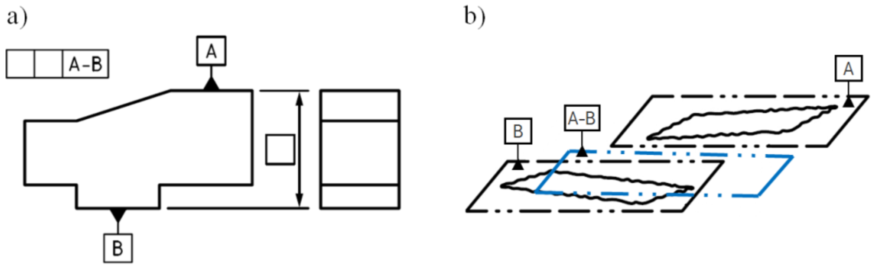

Fig. 3. a) single datum plane A and B, b) illustration of the establishment of the common datum A-B [1]

- *Complementary indication: if all the situation features* [16] *(plane, line or point) of datum are not required, the appropriate amount of complementary indications ([PL] plane, [SL] straight line, [PT] point) should be added after the datum letter symbol* [1]. For example [PL][SL] when a plane and straight line are required.

2.2. ORIENTATION CONSTRAINTS AND 3-2-1 PRINCIPLE

The centred part alignment with centred points is based on the thought model of the 3-2-1 principle [17,18], which constrains all 6 degrees of freedom (DOF) of a part in space. The 6 DOF contains three translations in X, Y and Z direction and 3 rotations around each axis [12,17,18]. Fig. 4 illustrates this principle. Wherein, based on the rule of ISO the primary datum imposes orientation constraints on the secondary datum and tertiary datum; the secondary datum imposes orientation constraints on the tertiary datum [1]. So in Fig. 4a the primary datum plane is established by three datum targets, the secondary datum plane is built by two points and the normal vector of the primary plane and the third plane is formed with the normal vectors of the primary and secondary planes and a point. Those three datums are generally considered as: primary datum plane; secondary datum line where the primary and secondary datum planes intersect or a line which is parallel to the intersection line; tertiary datum point is the intersection point of primary, secondary and tertiary datum planes (Fig. 4b).

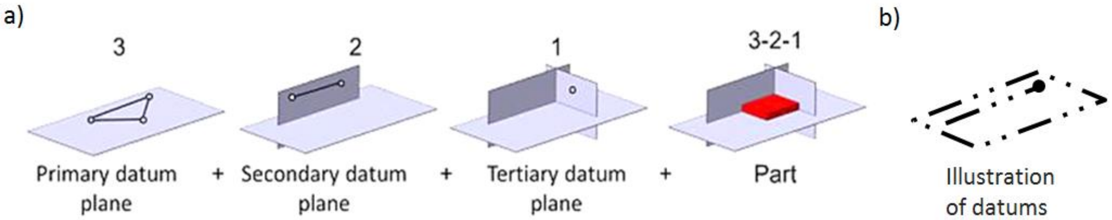

Fig. 4. a) 3-2-1 principle including orientation constraints, b) illustration of datums [1,18]

2.3. DATUM TARGET BY CENTRED PART ALIGNMENT

Based on ISO the centred part alignment with derived geometrical element [16] shall be aligned with fixed datum targets. Fig. 5 shows a centred part (cylinder) alignment which is aligned with the middle line (axis) as a datum by using the fixed datum targets A1, A2 and A3.

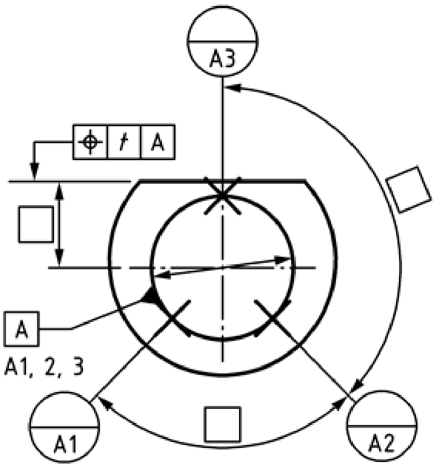

Fig. 5. Centred part alignment with middle line by using fixed datum targets A1, A2 and A3 [1]

3. DEFICITS OF THE ISO BASED METHOD

The terminology deficits in this paper means that the ISO based method does not fully consider every situation by centred part alignment with centred point and some definitions are ambiguous, which causes corresponding limitations and space for interpretations. This section subdivides three examples of components of increasing complexity by analysing the deficits of centred part alignment imposed by ISO for each. The first example is a cube where its centred part alignment uses only one centred point; the second example is a U-shaped part with two centred points established from two parallel planes; the third example is a U-shaped part with two centred points established from four parallel offset planes.

3.1. CUBE: CENTRED PART ALIGNMENT WITH ONE CENTRED POINT

Centred part alignment with one centred point means a part is aligned with a middle point as datum which is established through a centring process. Fig. 6a illustrates a cube with its alignment. Fig. 6b shows its possible corresponding technical drawing based on ISO (Note: due to the clarity of the drawings, the theoretical exact dimensions (TED) are omitted in the following figures [1]). Fig. 6c illustrates the datums of the cube. The datum system can be recognised in the tolerance frame of the position tolerance [19]. The cube is located firstly on the primary datum plane A which constrains the Z translation and rotations around Y and X axes. Then the cube is shifted to the datum targets B1 and B2, which have equal length in the Z direction and through these points jointly establish the secondary datum line B (Fig. 6c). This datum line constrains the Y translation and rotation around the X axis. Based on the ISO notation of datum targets, B1,2 shall be noted near to the datum feature indicator in the technical drawing. Now the only remaining DOF for the cube is the X translation. The tertiary datum point C-D (blue point in Fig. 6c) is the centred point in between the fixed datum targets C1 and D1 from two different datum feature surfaces. Based on ISO different datum letters shall be used on different datum feature surfaces. The first deficit is revealed when Fig. 6b is compared alongside Fig. 6c. There is no explicit definition in ISO on whether the datum feature indicator is positioned directly on the datum line / point (Fig. 6c) or on the surface of them (Fig. 6b). For example, the datum feature indicator B is drawn on the side surface of the cube in Fig. 6b, but in Fig. 6c it is drawn directly on the secondary datum line. These two potential notations for the datum feature indicator B in the technical drawing can result in the reader misunderstanding whether the datum is a plane on the surface or a line on the surface. This deficit exists in the three examples given below by all possible ISO technical drawings in Fig. 6, 7 and 9.

Deficit 1: When following ISO it is not explicitly defined where to position the notation of the datum feature indicator of a datum line or a datum point on the surface in the technical drawing to convey accurate meaning

The second deficit is revealed upon the alignment of the last DOF by using the two fixed datum targets C1 and D1. The surfaces of the cube which contain the fixed datum targets C1 and D1 have surface tolerance [12] of 0.5 mm in Fig. 6b. Theoretically, it is impossible to manufacture a perfect part without tolerances and therefore the cube will never be manufactured as a perfect fit in between the two fixed datum targets. It will be either manufactured too large or small for this gap. As a result, upon practical alignment the part will not be sufficiently constrained.

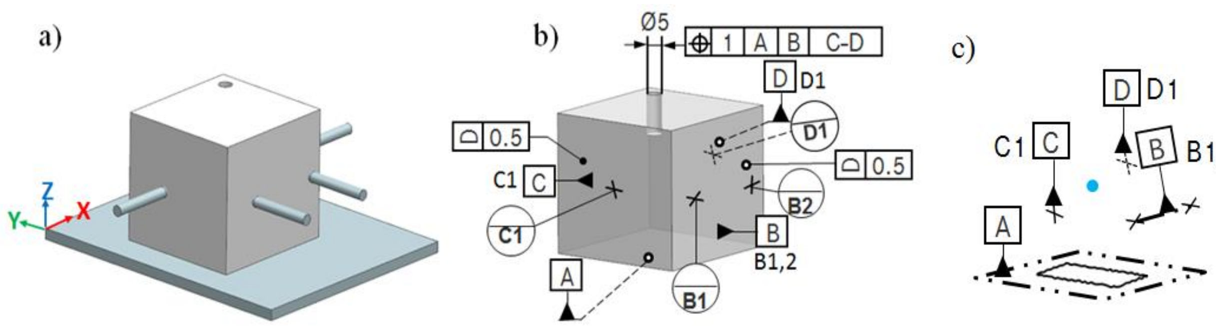

Fig. 6. a) alignment of the cube, b) possible technical drawing based on ISO, c) illustration of datums [1]

Deficit 2: Fixed datum targets based on ISO cannot function for a toleranced part when used for centred part alignment with the centred point

3.2. U-SHAPED PART: CENTRED PART ALIGNMENT WITH TWO CENTRED POINTS ESTABLISHED FROM TWO PARALLEL PLANES

Centred part alignment with two centred point means a part is aligned with two middle points which are established through a centring process in the alignment. In order to analyse the deficits of centred part alignment with two centred points, the U-shaped part is illustrated in the Fig. 7. In analogy to the cube, the U-shaped part locates firstly on the primary datum plane A-B (Fig. 7c) which is established from the single datum planes A and B. A-B is parallel to the plane XY. Datum planes A and B are established from the entire datum features which results in an unstable datum plane establishing process. This deficit will be explicated at the end of the subsection 3.2. The U-shaped part is now shifted to the four fixed datum targets C1, C2, D1 and D2 which are located on two parallel planes. The part cannot be exactly aligned because of the deficit of the fixed datum targets which are described above. C1 has a different length in the Z direction to C2, whereas C1 and C2 have the same length as D1 and D2 respectively. It leads that the established single datum lines C and D are inclined and mutually parallel, which are illustrated by the blue lines in Fig. 7c. The four fixed datum targets are used to establish the secondary datum line whose notation is currently missing in the tolerance frame in Fig. 7b imposed by ISO. This deficit will be explicated in detail in Fig. 8. The last DOF is constrained by the tertiary datum point E1 on the thickness plane.

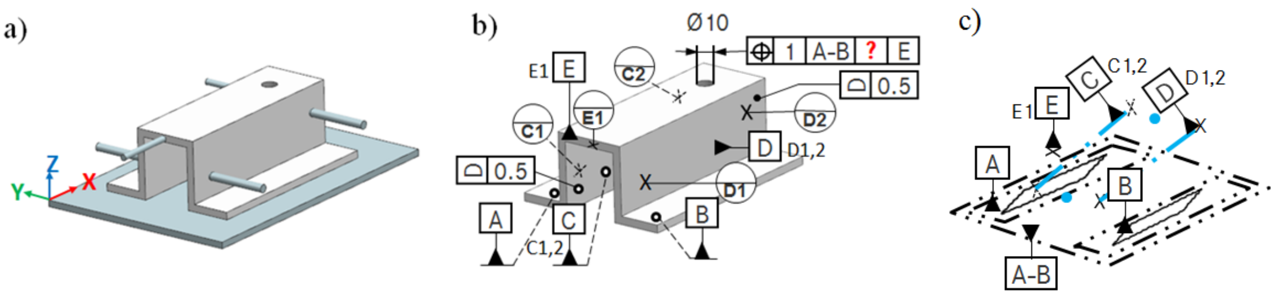

Fig. 7. a) alignment of the U-shaped part, b) possible technical drawing based on ISO, c) illustration of datums [1]

Fig. 8 shows the side-view of the U-shaped part. The blue points in Fig. 8 illustrate the centred points of C1 and D1, C2 and D2, which are also drawn in Fig. 7c. Here a dash-dot-dot line illustrates a possible secondary datum line according to the notation in the tolerance frame [19]. For reference, the primary datum plane is parallel to plane XY. Based on the orientation constraints between the primary and secondary datum, which are described in subsection 2.2, the secondary datum line must remain parallel to the X axis (black dash-dot-dot line in Fig. 8a). This datum line can be either through the centred point of C1 and D1 or through the centred point of C2 and D2, both of which are correct. However, based on ISO the correct secondary datum line cannot be notated in the tolerance frame. Fig. 8b shows the current notation following ISO for C-D (common datum line) in the tolerance frame, however this incorrectly illustrates the secondary datum line as the inclined centred lines of C and D (blue dash-dot-dot line in Fig. 8b and Fig. 7c).

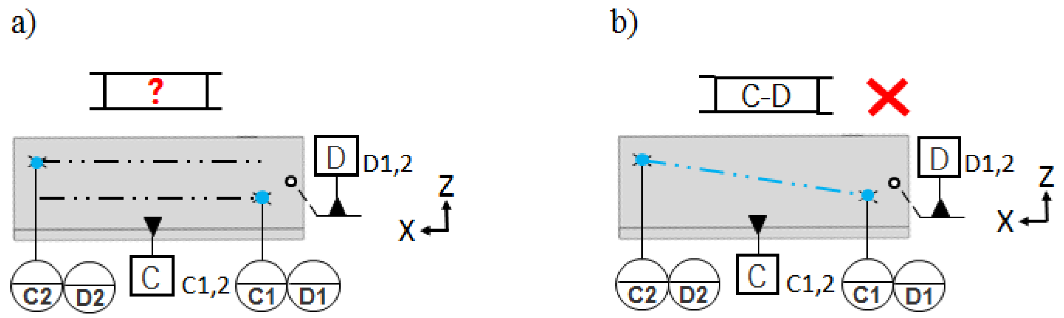

Fig. 8. Blue point; centred point; black dash-dot-dot line; correct secondary datum line; blue dash-dot-dot line; incorrect secondary datum line; - a) correct secondary datum line which cannot be notated in the tolerance frame, b) incorrect secondary datum line with notation C-D in the tolerance frame

Deficit 3: Secondary datum line cannot be notated in the tolerance frame currently imposed by ISO when the part is aligned using two centred points

Another deficit exists whereby ISO currently uses a plane across two entire datum feature surfaces A and B to establish the primary datum plane A-B. In practice, two U-shaped parts cannot be manufactured as exactly identical due to manufacturing tolerances. Therefore, when putting two U-shaped parts in the same alignment one after another, the touched points of the datum feature surfaces A and B in each U-shaped part are different. This results in the datum plane A-B to be established differently for each part, which puts at risk the reproducibility when establishing the datum plane.

Deficit 4: Irreproducible datum plane establishing process due to the usage of the entire datum features

3.3. U-SHAPED PART: CENTRED PART ALIGNMENT WITH TWO CENTRED POINTS ESTABLISHED FROM FOUR PARALLEL OFFSET PLANES

A more complicated case of centred part alignment with two centred points which is established from four parallel offset planes is illustrated in Fig. 9. In analogy to the cube and the U-shaped part of subsection 3.2, it has the deficit 1, 2, 4 as well. The difference between the U-shaped part in Fig. 7 and the following Fig. 9 is: the fixed datum targets C1, D1, E1 and F1 are in four different parallel offset planes. That is why they must be written with different datum letters and different datum feature indicators based on ISO. It means that, the four fixed datum targets establish four individual datum points as shown in Fig. 9c. All the four datum points contribute to establish the secondary datum line. However, the notation of the secondary datum line is still unknown according to the definition of ISO. This problem is an extension of deficit 3.

Fig. 10 is the top-view of the U-shaped part which illustrates the possibilities of the notation of the secondary datum line in the tolerance frame. Due to the orientation constraint between the datum's, the secondary datum line must be parallel to the X axis which is already explicated above.

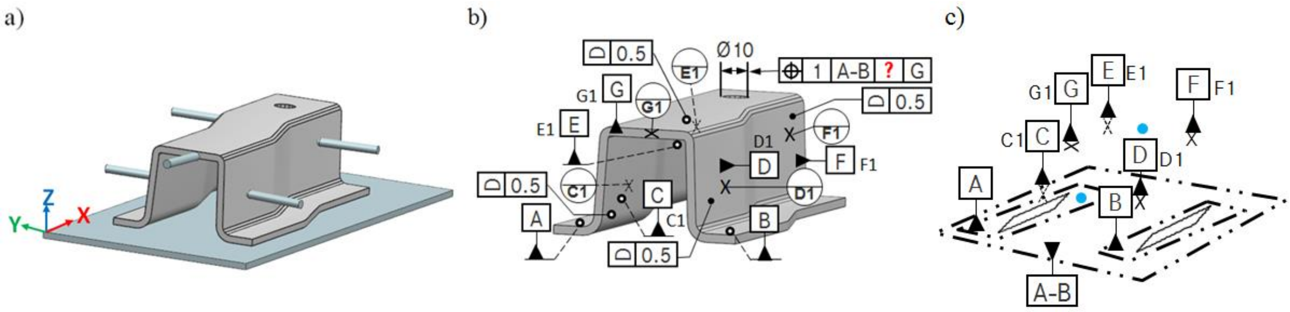

Fig. 9. a) alignment of the U-shaped part, b) possible technical drawing based on ISO, c) illustration of datums [1]

The black dash-dot-dot line in Fig. 10a illustrates all correct secondary datum lines. In Fig. 10b the centred point (blue point) of C1 and D1 is written as (C-D), in the same the centred point of E1 and F1 is written as (E-F). So their common datum (C-D)-(E-F) means the centred point of (C-D) and (E-F) would be the middle blue point in Fig. 10b. This point is not the correct secondary datum. Fig. 10c shows another possibility to notate the secondary datum line which uses the complementary indication [SL] after the common datum. But, this results in an inclined line which is directly through the two centred points and this is also an incorrect secondary datum line.

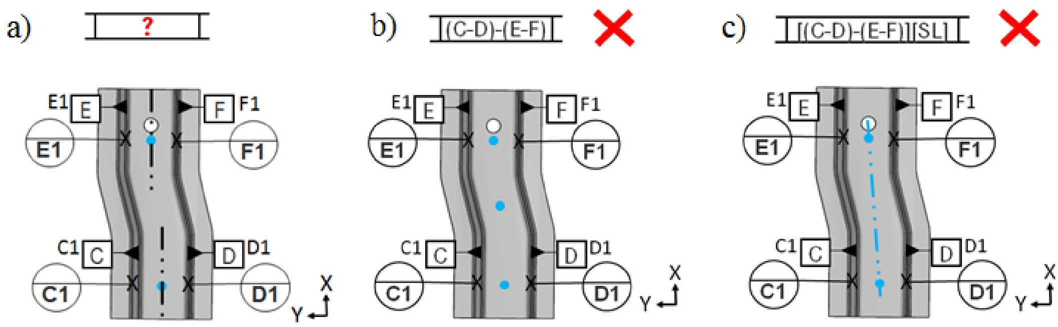

Fig. 10. Blue point; centred point; black dash-dot-dot line; correct secondary datum line; blue dash-dot-dot line; incorrect secondary datum line; - a) correct secondary datum line which cannot be notated in the tolerance frame, b) common datum point as an incorrect secondary datum, c) inclined and incorrect secondary datum line

4. NEW APPROACH

This section proposes a new approach by using the example of the U-shaped part with four different parallel offset planes. This part contains all the four deficits described above and contains the most complex geometry in this paper. The approach offers a new notation system of the datum targets, datum’s and datum systems based on the analysis of the orientation constraints and the physical behaviour of the centred part alignment with centred points. The purpose of this new approach is to eliminate the above deficits, provide explicit and simplified technical drawing and stabilize the datum establishing process.

Fig. 11 shows the alignment, corresponding new notation system and the illustration of the datums. The primary datum plane, secondary datum line and tertiary datum point remain the same as in ISO, but the notation system (inclusive of numeration) is edited in the new approach. The following subsections 4.1, 4.2 and 4.3 explicate the improvements of the new approach and compare these alongside the ISO method hierarchically by primary, secondary and tertiary datums.

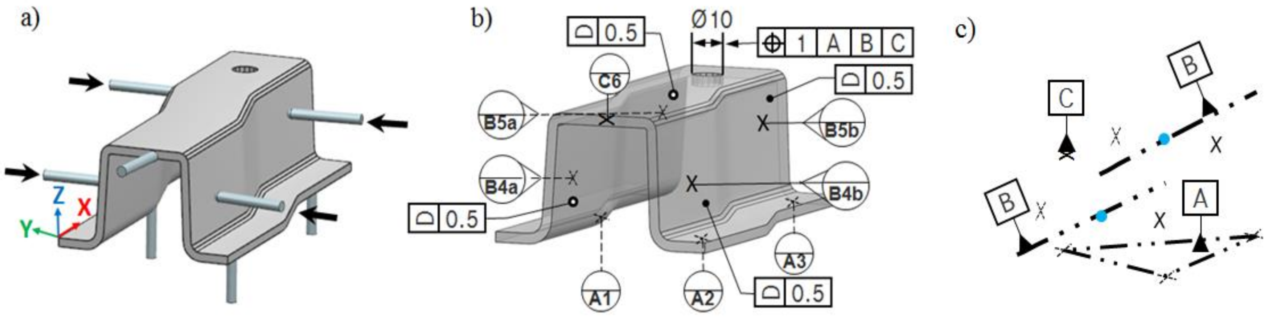

Fig. 11. a) proposal of the new alignment, b) new notation system in the technical drawing, c) illustration of the datums

4.1. IMPROVEMENTS OVER PRIMARY DATUM PLANE

Fig. 12a shows the notation of the primary datum plane A-B based on ISO. Fig. 12b shows the notation of the primary datum plane A based on the new approach. Fig. 12c shows the illustration of the primary datum plane A according to the new approach. Both established datum planes, A-B and A, are mathematically and functionally identical and are both parallel to the plane XY and constrain the same DOF. The normal vectors of datum planes A and B also have the same direction. So, the common datum plane A-B is identical to datum planes A and B. That is why in the new approach, only the datum letter A is applied on both datum feature surfaces. The datum letter A is implemented throughout the three explicitly defined datum targets A1, A2 and A3, which is the number of mathematically required datum targets to establish an explicitly defined plane.

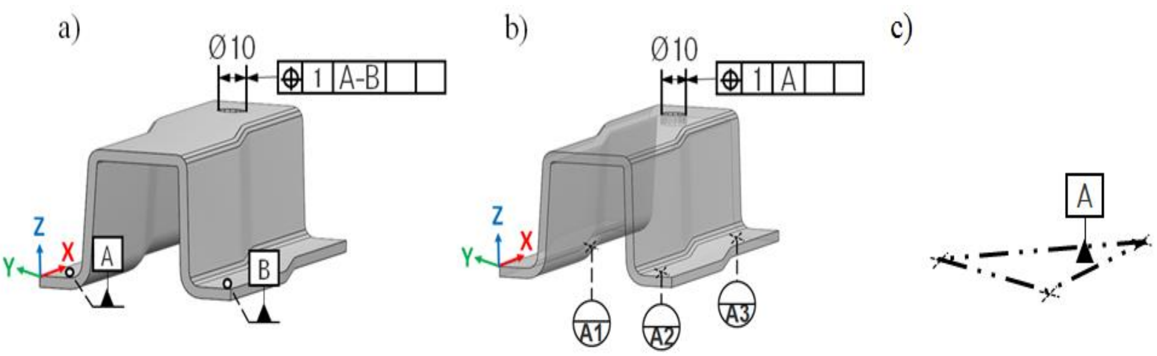

Fig. 12. a) notation system based on ISO for primary datum plane A-B, b) notation system based on new approach for primary datum plane A, c) illustration of explicitly defined primary datum plane A based on new approach

Utilizing these explicitly defined datum targets, the deficit 4 can be eliminated. The datum feature indicators (for definition see subsection 2.1) can be omitted because of the simplicity and explicit understanding that there exists only one primary datum plane, A, within the technical drawing. Moreover, the datum feature indicators are not required for the measuring process, since the measurement technicians need only the datum targets to measure a part in space rather that the datum feature indicator.

Improvements:

1. Primary datum plane is simplified and written as A.
2. Same alphabetical character A is applied on the two functionally identical datum feature surfaces, even though they are physically different planes.
3. Explicitly defined datum targets are used to establish the explicitly defined primary datum plane, instead of the entire datum features.
4. Datum feature indicators are omitted

4.2. IMPROVEMENTS OVER SECONDARY DATUM LINE

According to the orientation constraint, the secondary datum line is parallel to the X axis; which cannot be notated in the tolerance frame based on ISO (Fig. 13a). The new approach provides a suggestion for the secondary datum line in Fig. 13b with usage of the single datum character B. Fig. 13c illustrates the correct secondary datum line B and the centred points B4a and B4b, B5a and B5b. The secondary datum line is established by the moveable datum targets B4a, B4b, B5a and B5b from four different surfaces. They all contribute to establish the secondary datum line, so functionally they can all use the same alphabetical character B, instead of four different alphabetical characters C, D, E and F. The movement direction of the movable datum targets is specified by the median segment of the movable modifier [1]. The black arrows in Fig. 11a illustrate these movement directions of the moveable datum targets in the alignment. The usage of the movable datum targets by centred part alignment with the centred points eliminates the deficit 2 in which the body is not sufficiently constrained by the alignment process. The U-shaped part is aligned physically using the two centred points of B4a and B4b, B5a and B5b (the blue points in Fig. 13c). To illustrate which points should be used for the centring process, the small letters a and b are added to identify each pair. The thought model for the position of the secondary datum line states that: it can pass through either the centred point of B4a and B4b, or the centred point of B5a and B5b. If the datum establishment theory is explicitly defined, then the application of the single datum letter B in the tolerance frame can also be clearly defined and understood. As a result, the deficit 3 can also be eliminated. The U-shaped part has a total of 6 DOF. The primary datum plane blocks the first, second and third DOF and the secondary datum line blocks the fourth and fifth DOF. To illustrate this, the moveable datum targets are notated with the numbers 4 and 5 for each DOF blocked, respectively. The datum feature indicators are omitted because of the same reason as explained in subsection 4.1. Due to the omission, the deficit 1 is eliminated as well.

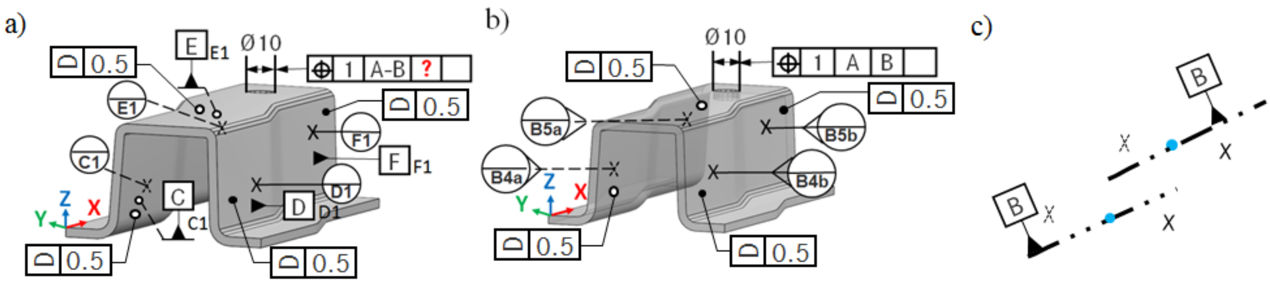

Fig. 13. a) notation system based on ISO for secondary datum line, b) notation system based on new approach for secondary datum line, c) illustration of the secondary datum line based on new approach

Improvements:
1. Secondary datum line is simplified and written as B.
2. Same alphabetical character B is applied on the four functional identical planes.
3. Moveable datum targets are applied to the centred part alignment.
4. New numeration system of the datum targets offers a function-oriented, clarified and simplified technical drawing.
5. Datum feature indicators are omitted.

4.3. IMPROVEMENTS OVER TERTIARY DATUM POINT

Fig. 14 shows the notation of the tertiary datum point imposed by ISO and by the new approach. Fig. 14c illustrates the tertiary datum point. The Tertiary datum point constrains the sixth (last) DOF, for this reason, the number 6 is added after the datum letter C in the datum target C6 following the new approach. Additionally, the datum feature indicator is not required for the measuring process, since the measurement technicians need only the datum target to measure a part in space rather that the datum feature indicator.

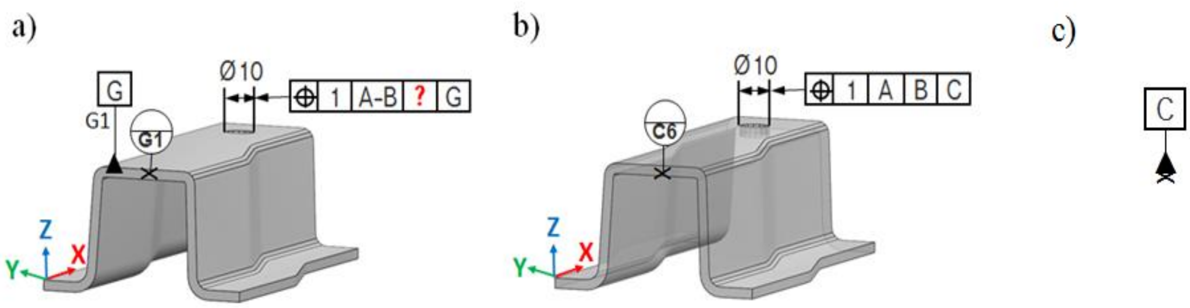

Fig. 14. a) notation system based on ISO for tertiary datum point, b) notation system based on new approach for tertiary datum point, c) illustration of the tertiary datum point based on new approach

Improvements:
1. New numeration system of the datum targets which offers a function-oriented, clarified and simplified technical drawing.
2. Datum feature indicators are omitted.

5. CONCLUSION

This paper presented a novel notation system of the datum targets, datums and datum systems for the centred part alignment with centred points. This new approach uses three explicitly defined datum targets on the primary datum feature surfaces, to avoid the irreproducible datum establishment process. The moveable datum targets are implemented to align the part with the centred points, in order to avoid an insufficiently constrained part. The explicitly defined new notation (inclusive of numeration) system solves the missing notation definitions imposed by ISO and offers a function-oriented, clarified and simplified technical drawing. In the new approach all the datum's are established from the movable and fixed datum targets which can be easily used in the measurement process. Future work involves applying the proposal to other complex geometry.

REFERENCES

[1] ISO 5459, 2011, *Geometrical Product Specification (GPS)-Geometrical tolerancing-Datums and datum systems.*

[2] HUMINENNY Z., 2009, *State of art in standardization in GPS area,* CIRP Journal of Manufacturing Science and Technology, 2/1, 1-7.

[3] ISO 14660-1, 1999, *Geometrical Product Specification (GPS)-Geometrical features-Part 1: General terms and definitions.*

[4] ADRAGAN P., SAMPER S., PILLET M., FAVRELIERE H., 2006, *Analysis of shape deviations of measured geometries with a modal basis,* Journal of Machine Engineering, 6/1, 134-143.

[5] ANSELMETTI B., LOUATI H., 2005, *Generation of manufacturing tolerancing with ISO standards,* International Journal of Machine Tools and Manufacture, 45/10, 1124-1131.

[6] BHAT V., C DE METER E., 2000, *An analysis of the effect of datum-establishment methods on the geometric errors of machined features,* International Journals of Machine Tools & Manufacture, 40/13, 1951-1975.

[7] GASKA A., SLADEK H., 2016, *Modelling of the coordinate measurement system accuracy,* Journal of Machine Engineering, 16/3, 34-46.

[8] GREEN P., 2005, *The Geometrical Tolerancing Desk Reference. Creating and Interpreting ISO Standard Technical Drawings*, 1st Edition, ISBN 978-0080460857, Elsevier.

[9] HENZOLD G., 2006, *Geometrical Dimensioning and Tolerancing for Design Manufacturing and Inspection,* Butterworth-Heinemann.

[10] JORDAN W., 2008, *Form- und Lagetoleranzen: Handbuch für Studium und Praxis,* Hanser Verlag, ISBN 978-3446430808, Germany.

[11] JORDAN W., SCHÜTTE W., 2014, *Form- und Lagetoleranzen: Handbuch für Studium und Praxis,* Hanser Verlag, ISBN 978-3446439702, Germany.

[12] MEJBRI H., ANSELMETTI B., MAWUSSI K., 2005, *Functional tolerancing of complex mechanisms: Identification and specification of key parts,* Computer & Industrial Engineering, 49/2, 241-265.

[13] SHAKARJI C., SRINIVASAN V., 2016, *Theory and algorithm for planar datum establishment using constrained total least-squares,* 14th CIRP Conference on Computer Aided Tolerancing (CAT), 232-237.

[14] ZHANG X., ROY U., 1993, *Criteria for establishing datums in manufactured parts,* Journal of Manufacturing Systems, 12/1, 36-50.

[15] BOHN M., HETSCH K., 2016, *Funktionsorientiertes Toleranzdesign,* Hanser Verlag, ISBN 978-3446450097, Germany.

[16] ISO 17450-1, 2011, *Geometrical Product Specification (GPS)-General concepts-Part 1: Model for geometrical specification and verification.*

[17] ASME Y14.5, 2009, *Dimensioning and Tolerancing- Engineering Drawing and Related Documentation Practices.*

[18] BOHN M., HETSCH K., 2013, *Toleranzmanagement im Automobilbau,* Hanser Verlag, ISBN 978-34446434967, Germany.

[19] ISO 1101, 2013, *Geometrical Product Specification (GPS)-Geometrical tolerancing-Tolerances of form, orientation, location and run-out.*