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Tolerances in micro manufacturing

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Abstract

This paper describes a method for analysis of tolerances in micro manufacturing. It proposes a mapping of tolerances to dimensions and compares this with current available international standards. The analysis documents that tolerances are not scaled down as the absolute dimension. In practice a tolerance level of 10 - 100 µm seems to be the preferred level no matter the absolute dimension.

Keywords: Specification, Tolerance, Micro

1. Introduction

Product development includes definition of concepts and detailed designs including specification. Specifications typically include dimensions, geometries, surface quality, material properties etc. Furthermore, specifications are usually equipped with tolerances stating maximum deviations from an ideal geometric form in this way governing functionality of the component (e.g. mating capability, sliding and rolling capability, load rating and different surface finishes). At the same time, tolerances are used as information for the manufacturing units in order to choose and regulate processes to the appropriate level. Finally, tolerances are used together with the final quality control of the component to determine whether the component meets specifications or not (illustration Figure 1). This closed loop system is very well established in conventional manufacturing. Here various ISO standards regulate this field in terms of Geometrical Product Specifications (GPS) e.g. [1]. These standards describe the entire sequence from specification over choice of measurement equipment to final evaluation of the results. GPS standards follow a set of well-founded axioms and principles.

Previous researchers have done intensive work on how to determine geometrical tolerances, for example, Weckenmann described his computer-aided method for geometrical tolerancing in [2]. This paper aims at pointing out the mostly used tolerances range based on experiences from our researches with industrial partners. The method is to collect and map tolerances to dimensions of specific products. Meanwhile the data are sorted by T/d ratio (Tolerance / dimension). The trend is notable that T/d ratio can be used to set up tolerance based on the dimension range.

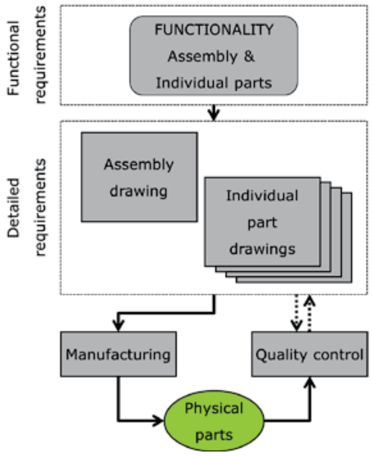

Figure 1 Connection between specification, manufacturing and quality assurance.

2. Tolerancing

The activity of defining and setting tolerances is a natural part of the product design process. It is also the level of detail that links the function, the manufacturing and the quality assurance. Therefore, the activity becomes extremely important. The ability to set a meaningful tolerance is of utmost importance for the subsequent manufacturing steps and resulting product performance. The last step of the design process is to set the specific tolerances for specific features and components expressing the engineering intent of these parts and assemblies. According to [3] the term tolerance (T) is defined as “the difference between the lower and upper tolerance limit”. The tolerancing limits are “specified values of the characteristic giving upper and/or lower bounds of permissible value”. Tolerances on dimensions can be symmetrical or non-symmetrical. Geometrical tolerances describe maximum allowable deviation from an ideal shape. A tolerance zone does not necessarily specify the part surface behaviour inside the zone. The smaller the tolerance zone, the smaller the allowable variations and therefore the less freedom in terms of surface deviations. Figure 2 illustrates a typical dimensional tolerance.

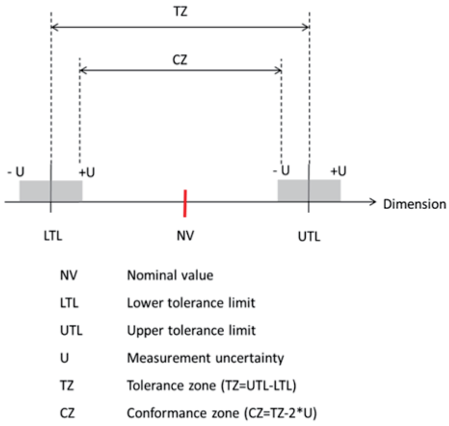

Figure 2 Symmetrical dimensional tolerance

The dimensional tolerance system as defined in ISO 268 [4][5] is established to govern mechanical functions of construction elements such as mating capability, sliding and rolling capability etc. Table 1 presents a summary of these standards. The first observation is that all sizes below 3 mm are grouped into one category. Next observation is related to the fact that tolerance values below 10 µm dominate approximately 50% of the fine tolerance grades (IT values). It can even be seen that some of these are on the nm level. At the other end of the scale a tolerance of 1 mm on a 3 mm dimensions also seems impractical. The usefulness of such values from a specification point view is doubtful. Considering also that at small scales size effects come into action [6], these principles and standards cannot be recommended for setting tolerances related to function at this scale. However, both dimensional tolerances [4][5], geometrical tolerances [7] as well as surface texture standards are extremely useful in connection with defining and controlling manufacturing processes and establishing a quality assurance system.

A collection of information of various micro scale products and their related dimensional tolerances is presented in Figure 3. The information is collected over a period of 15 years from various industrial partners of the authors and the data is based on best practice from a large number of companies and individual designers. When in dialogue with practitioners in this field they state that typically tolerances are set by experience.

Figure 3 illustrates the findings of the analysis: The ISO standard 286 [4] is represented by solid green lines. The tolerance grades (differentiated by gradient shades of green) express the magnitude of the tolerance for a certain dimension interval. Higher grade number, for instance IT18, relates to higher tolerance values for the same dimension. Lower grades correspond to smaller absolute tolerance values. There is only one tolerance category when the dimension is less than 3 mm.

The tolerances and dimensions from practical cases are plotted by red triangular dots for metallic parts, blue square dots for plastic parts and orange circular dots for ceramic parts. T/d (Tolerance/dimension) ratios are indicated by dashed lines to illustrate whether the tolerances scale at the same rate as the dimensions. When the T/d ratio is more than 100% the tolerance is impractical, even though some cases exist in reality [8].

When the dimension is below 1 mm, for most of the studied cases, the tolerance is above 10% of the dimensions. In contrast, when the dimension is more than 1 mm, the tolerances drop until barely 1% of their dimensions. For the components with critical dimension more than 10 mm, the tolerance are even smaller in the sense or T/d ratio. However, they may correspond to higher grade numbers of the standard.

When the dimensions are below 10 µm, the tolerances are limited to the level corresponding to the very low grade numbers of the standard or even beyond the standard, while the T/d ratio does not similarly fall. For instance, the 3 polymer examples in the left end of the figure are the specifications of pits length on the surface of studied CDs [9]. They are defined to ensure the correct data transfer. The controlled functional parameters are time and scanning velocity, and they are transferred to a dimension by multiplying time and velocity. This permits the tolerance to expressed as a dimension and thus enables the verification from a dimensional metrological point of view. Their T/d ratios are slightly below 1%. However, the range of these tolerances are far below the border of the ISO standard.

One interesting phenomenon is that the tolerances are the same for dimensions in a certain range. For example, from 400 µm to 1 mm, there are a few cases with tolerance 40 µm; from 850 µm to 5 mm, there are a few cases with tolerance 100 µm. It shows that some of those tolerances may be from experience instead of being based on physical function requirements.

Most of the polymer parts plotted in this figure are produced by injection moulding. The range of the tolerance upper/lower limit is from 10 to 50 µm, since milling, EDM or other so-called conventional processes produced moulds for those parts. The tolerances are defined by functions, but also limited by those processes. Metal parts are produced by a variety of processes. For example, the most left case represents a 2-µm-deep hole with a tolerance 1 µm [10], which was produced by a lithographical process starting from silicon substrate. This type of process allows much finer tolerances and smaller T/d ratio can be achieved.

Table 1. Standard tolerance values according to ISO 286 for nominal dimensions less than 50 mm and tolerance grades IT01-IT18 [3][4]

	IT 01	IT 0	IT 1	IT 2	IT 3	IT 4	IT 5	IT 6	IT 7	IT 8	IT 9	IT 10	IT 11	IT 12	IT 13	IT 14	IT 15	IT 16	IT 17	IT 18
Nominal dimension [mm]	Standard tolerance values [µm]													Standard tolerance values [mm]						
d≤ 3	0.3	0.5	0.8	1.2	2	3	4	6	10	14	25	40	60	0.1	0.14	0.25	0.4	0.6	1	1.4
3<d≤6	0.4	0.6	1	1.5	2.5	4	5	8	12	18	30	48	75	0.12	0.18	0.3	0.48	0.75	1.2	1.8
6<d≤10	0.4	0.6	1	1.5	2.5	4	6	9	15	22	36	58	90	0.15	0.22	0.36	0.58	0.9	1.5	2.2
10<d≤18	0.5	0.8	1.2	2	3	5	8	11	18	27	43	70	110	0.18	0.27	0.43	0.7	1.1	1.8	2.7
18<d≤30	0.6	1	1.5	2.5	4	6	9	13	21	33	52	84	130	0.21	0.33	0.52	0.84	1.3	2.1	3.3
30<d≤50	0.6	1	1.5	2.5	4	7	11	16	25	39	62	100	160	0.25	0.39	0.62	1	1.6	2.5	3.9
50<d≤80	0.8	1.2	2	3	5	8	13	19	30	46	74	120	190	0.3	0.46	0.74	1.2	1.9	3	4.6

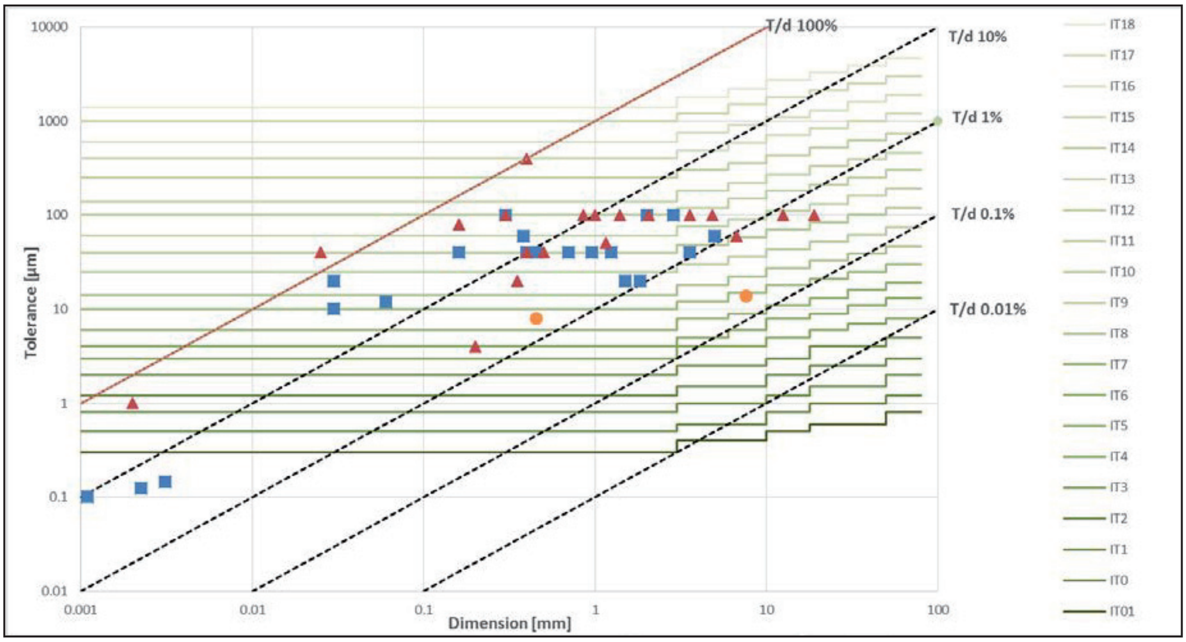

Figure 3 Tolerance vs. dimension. The blue square dots are for polymer parts, the red triangular dots are for metal parts; the orange circular dots are for ceramic components. the green lines shows the tolerance values for different dimension range in ISO 286 standard, while the different shade of green stands for different tolerance grades. The dashed lines are contour plots for Tolerance/ dimension ratio. [4], [8]-[18]

4. Case study

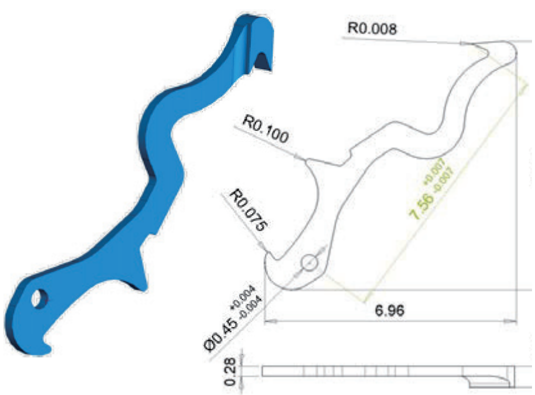

Figure 4 A ceramic knocker for high-end watch. Two critical dimensions with symmetric tolerances are noted in the drawing [11].

A specific study case of a micro mechanical part with defined specifications is illustrated in Figure 4 [11]. The investigated product is a knocker for high-end watch industry, which is a critical functional component in a high-accuracy miniaturised mechanism. Some of the identified challenges involved in the production are the radius R 0,008 mm, the geometrical shape, the surface quality, and the two critical dimensions with tolerances:

- The inner diameter of the hole: 0.45 ± 0.004 mm (T/d = 1.8%)
- The length from the center of the hole to the tip: 7.56 ± 0.007 mm (T/d = 0.2%)

Ceramic powder injection moulding was used for the production of the part in order to improve the wear resistance, to achieve the required surface finish and to make the part with the dimensional precision required for the application.

For the investigated length of the part, the tolerance is 14 µm, which is close to class IT7 in the standard. The function of this length is to fit the tip precisely to the groves of the gear wheel inside the watch. The T/d ratio is as low as 0.2%. This is challenging for both the manufacturing process and the quality assurance process. It must be ensured that the measurement uncertainty [19][20] is sufficiently small to be able to verify the tolerance.

The inner diameter of the hole on the part is below 1 mm. The upper/lower tolerance limit is 4 μm. This dimension is important for the robust fitting of the knocker inside the mechanical system of the watch and to prevent generation of any additional noise raise from the loose fitting of the components. Both the above-mentioned dimensions are important for making a precise and sophisticated “tick” sound by the watch. This tolerance corresponds to class IT7 as well. When the dimension is below 3 mm, there is no variance for the standard. However, the T/d ratio is approximately 2% that is 10 times more than the one for the length, even though both tolerances are several microns.

5. Conclusions

This paper describes a method for analysis of tolerances in micro manufacturing. Based on practical cases from various industrial partners, tolerances are plotted against dimension of the specific product. Meanwhile the data are sorted by the T/d ration (tolerance / dimension). In this way, it is possible to visualize how tolerances was set when the dimension decreased down to micro range. The analysis documents that tolerances are not scaled down as the absolute dimension. In practice, experience of the designer plays a role when they set up the tolerance for the product at micro range scale. When the dimension is below 1 mm, T/d value of 10% is very common; when the dimension is more than 1 mm (below 10 mm), 1% seems to be a limit for T/d ratio. Tolerance level of 10 - 100 μm seems to be the preferred level no matter the absolute dimension.

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