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The Discussion of Uncertainties in Surface Texture during Design, Manufacture and Measurement

The Discussion of Uncertainties in Surface Texture during Design, Manufacture and Measurement

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Abstract The objective of this paper is to examine different uncertainties between design, manufacture and measurement in surface texture by carrying out a deeply discussion and seeking possible evaluation methods. The analysis of correlation uncertainty, specification uncertainty and measurement uncertainty is carried out. All possible contribute elements of the uncertainties are listed and examined with presently available knowledge. The relationships and management between these uncertainties are discussed based on the requirements of Geometrical Product Specifications (GPS). It concludes that a rigorous control of specification uncertainty in the early stage of the design process can significantly reduce the cost and avoid later disputes over acceptance or rejection of product. A management method to reduce specification uncertainty based on comprehensive analyse is proposed. A statistical evaluation method of the specification uncertainty for a specified case is proposed and tested. The ultimate aim of the paper is to link design, manufacture and measurement seamlessly by decreasing uncertainties between them; thus to remove chaos and reduce waste, and to underpin a rigorous and cost-saving manufacture supply chain.

1. Introduction

Surface texture plays a significant role in determining the function performance of workpiece because of the sensitivity of it to change in the process. The designers have the great responsibility of insuring the assigned surface texture specification will satisfy the function requirements. The assigned specification then will be interpreted by the engineers and inspectors to guide manufacture and measurement. However, the specification does not always truly express the function requirements; and most of the old existing definitions of ISO/GPS (Geometrical Product Specifications) standards leave a room for several different interpretations when the workpiece is not perfect in form and angle, and the implementation of the standards is not always without faults. The main work of ISO/TC 213 has been focusing on decreasing these ambiguities and imperfections. These issues, in other terms, are expressed as an extended uncertainty system defined in ISO/TS 17450-2:2002, where the concept of uncertainty is expanded from being something measurement related to being the universal currency for quantifying ambiguity in requirements, specification and verification, see Fig 1.

The uncertainty arising from the difference between the specified specification and the related function requirement is defined as correlation uncertainty. The incompleteness of the specification is defined as specification uncertainty. It was realized that disagreements on the measurement values cannot always be explained by the presence of conventional measurement uncertainty only. The extended measurement uncertainty is the combination of method uncertainty and implementation uncertainty. Method uncertainty expresses how well a selected verification process mirrors the specification. It occurs when the actual verification operators are compared to actual specification operators. Implementation uncertainty is only involved in the verification process, and it describes the accuracy of the instruments used, the influence of the environment, and the operator, etc.

In order to explore the extended uncertainties, ISO 14253 series have been published to estimate uncertainty for GPS measurement that introduces the novel idea of a target uncertainty and the PUMA (Procedure for Uncertainty MAnagement) method. The PUMA aims at proving the actual uncertainty is less than the target uncertainty with minimum effort, rather than estimating the actual uncertainty as accurately as possible. To evaluate measurement uncertainty, the updated GUM (Guide to the expression of uncertainty in measurement) introduced Monte Carlo method for evaluation [1, 2]. The concepts and methods given in GUM can without problems be

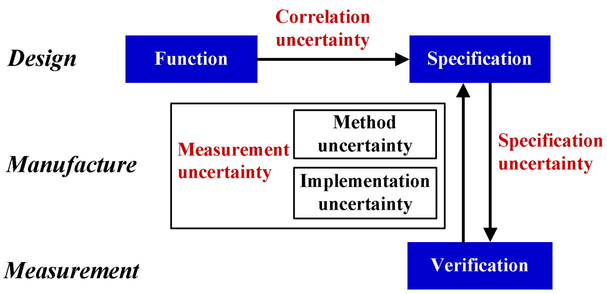


Fig. 1 Uncertainties between design, manufacture and measurement

used on the specification operator, and the resulting specification uncertainty values can therefore be compared with the corresponding measurement uncertainty values. However, the specification uncertainty values evaluated for specifications given on existing engineering drawings, generally are much larger (5-10 times or even more) than the 'normal' measurement uncertainty used for the measurements in industry to verify the conformance with the specification. Too many resources are used on measuring the wrong/unnecessary characteristic with a high precision, compared with the resources used on setting up proper specifications - having small specification uncertainty [3].

To this end, the analysis of correlation uncertainty, specification uncertainty and measurement uncertainty is carried out in this paper. All possible contribute elements of these uncertainties are listed and examined with presently available knowledge. The relationships and management between these uncertainties are discussed based on the requirements of GPS. It concludes that a rigorous control of specification uncertainty in the early stage of the design process can significantly reduce the cost and avoid later disputes over acceptance or rejection of product. A management method to reduce specification uncertainty based on comprehensive analyse is proposed. A statistical evaluation method of the specification uncertainty for a specified case is proposed and tested. The ultimate aim of the paper is to link design, manufacture and measurement seamlessly by decreasing uncertainties between them; thus to remove chaos and reduce waste, and to underpin a rigorous and cost-saving manufacture supply chain.

2. Uncertainties between design, manufacture and measurement in surface texture

2.1 Correlation Uncertainty

The designers have the great responsibility of insuring the assigned surface texture specification will satisfy the function requirements. However, some functions, such as engine scenario are very complex and almost impossible to express purely in terms of surface texture or geometry without having to be overly restrictive. In most cases, the assigned specification does not always truly related to the function requirements since it is really difficult to find a rigorous correlation. This difficulty, as described by Whitehouse is "perhaps the biggest inverse problem in manufacturing" [4]. The difference arises from a less than perfect correlation between a specification and the intended function of the workpiece, expressed in the term of correlation uncertainty.

It is however not very common to establish an evaluation approach for correlation uncertainty, although there is large amount of research concerning surface texture in function areas. The correlation uncertainty was rarely studied in engineering, not only because the related function situations are spread over every corner of engineering, but also it takes a number of specification items to simulate a function. The only correlation uncertainty research so far was proposed by Dantan [5]. In their study, a model for the expression and an evaluation method of the correlation uncertainty in the application of gear conformity has been proposed based on the Axiomatic Design matrix and the Monte Carlo Simulation.

The correlation uncertainty in surface texture, as shown in Fig 2, is caused by the lack of correlation between the functional input (including function requirements, component type and manufacturing process) and specification elements especially the surface texture parameters and their limit value. To clarify the large range of functions related to surface texture, Whitehouse [6] classified the functions and surface features using the separation of the surfaces and their lateral movement. This classification is an essential element in trying to understand how functional performance is influenced by the surface texture. However, identifying very specific parameters of the surface texture with function is still fraught with problems. Little or no convincing evidence is available to link very specific surface parameters to function. To accommodate this uncertainty, a usual option is to try a few parameters to get the best correlation between parameter and function, and then tighten the limit value, so that the workpieces in the grey zone will be rejected. A lower correlation uncertainty would obviously allow us to reject fewer potentially good parts.

2.2 Specification Uncertainty

Surface texture specification is the design step where control elements are stated, accommodating the design requirements of parts and their functional surfaces commensurate with production capabilities for the use of design and engineering drawings. It often is based on international, national standards or internal company standards. Sometimes the language of a standard is open to interpretation or gives equal value to choices that are not equivalent [7]. In those cases an ambiguity (interpreted as specification uncertainty) is built into the specification, in which you can reasonably interpret it in different ways and reach different results. Then the span between these results is the value of specification uncertainty.

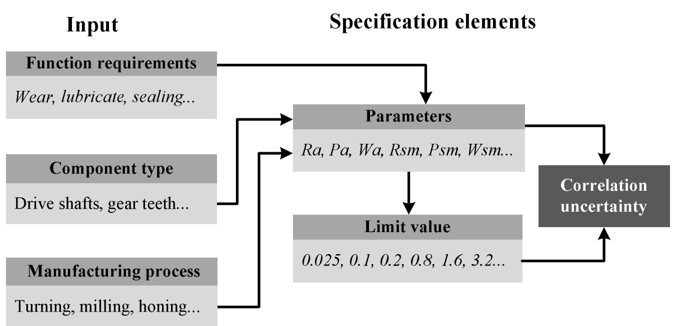
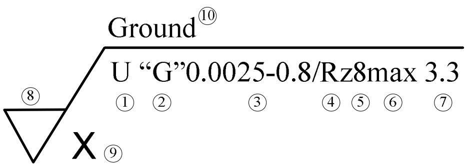


Fig. 2 Correlation uncertainty for surface texture



①Indication of upper (U) or lower (L) specification limit
②Filter type
③Transmission band
④Profile parameter
⑤Evaluation length as the number of sampling length
⑥Comparison rule
⑦Limit value in micrometres
⑧Type of manufacturing process
⑨Surface texture lay
⑩Manufacturing process

E_1 : E_{1-1}=U, E_{1-2}=L
E_2 : E_{2-1}=FPLG, E_{2-2}=FPLS, E_{2-3}=FPLW... E_{2-13}=F2RC
E_3 : E_{3-1}=0.0025-0.08, E_{3-2}=0.0025-0.25 ...E_{3-5}=0.025-8
E_4 : E_{4-1}=*Ra*, E_{4-2}=*Rq*, E_{4-3}=*Rz* ... E_{4-n}, $n \geq 62$
E_5 : E_{5-1}=3, E_{5-2}=4, E_{5-3}=5...E_{5-6}=8
E_6 : E_{6-1}=16%-rule, E_{6-2}=max-rule
E_7 : E_{7-1}=0.025, E_{7-2}=0.05, E_{7-3}=0.1...E_{7-m}, $m \geq 12$
E_8 : E_{8-1}="√" E_{8-2}="√" , E_{8-3}="√"
E_9 : E_{9-1}= "⊥", E_{9-2}= "=", E_{9-3}= "X"...E_{9-7}= "P"
E_{10} :E_{10-1}=Milling, E_{10-2}=Honing...E_{10-i}, $i \geq 9$

Fig. 3 Ten specification elements in the indication of profile surface texture according to ISO 1302:2002

Specification uncertainty in surface texture is usually caused by two factors: ambiguous definitions in standards and other requirement documents; and caused by designers who don't fulfil all the specification operators according to the related ISO or national standards. Examples of issues that can cause specification uncertainty in surface texture are as follows:

1. Ambiguous definitions in standards, for example parameter *RSm* definition given in ISO 4287:1997, different calculation directions cause different parameter results [8].
2. Absence of control elements. As shown in Fig. 3, there are ten different control elements for profile surface texture specification. The absence of any one or more of the elements will result in specification uncertainty.
3. Ambiguous understanding about default operations, e.g. default value of comparison rule in ISO and ASME is the "16%-rule", but in some internal company standards it is the "max-rule".

The first issue caused by the ambiguous in standards cannot be avoided in our case. The rigorous control of the specification elements and conscious explanation for default operations will be a better way to tackle the latter two issues.

A complete, unambiguous specification should enable metrologists to quickly discern implementation of the measurement easily. However, a complete specification is not one which specifies all of the possible measurement details, but rather one which can achieve communication with the verification, and with a minimum number of operations to give most measurement details.

2.3 Method uncertainty and implementation uncertainty

Method uncertainty (defined in ISO/TS 17450-2:2012), is the uncertainty arising from the differences between an actual specification operator and the actual verification operator, disregarding the physical deviations of the actual verification operator. This uncertainty accounts for the difference between what the specification calls for and what is implemented in the verification process, assuming the verification process has no physical deviations.

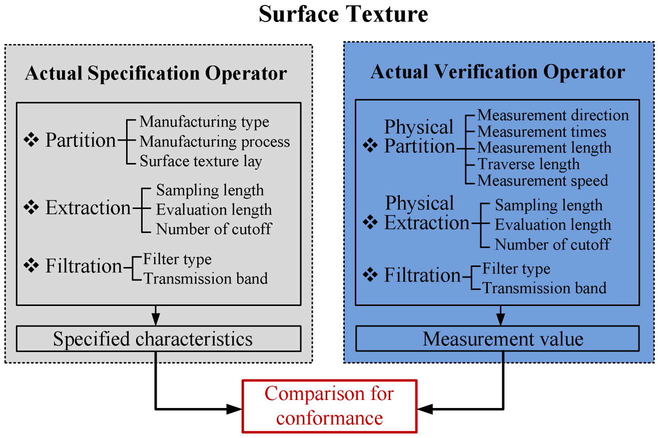


Fig. 4 Method uncertainty - difference between actual specification operator and actual verification operator.

As shown in Fig. 4, the actual specification operator of surface texture includes partition, extraction, filtration and evaluation operations (defined in ISO/TS 17450-2:2012). As there are only ten control elements in the profile specification, it is impossible and unnecessary to detail every measurement procedure and condition in these operations. The main sources of method uncertainty are from the difference of these operations between specification and verification and are listed below:

1. Difference between the partition operations of specification and verification. The partition operation in verification is composed of the measurement direction, number of measurements, measurement length, traverse length, measurement speed, etc. As not all of these verification operations are specified in the specification; the number of measurements, measurement length and traverse length can be determined by other control elements i.e. number of measurements can be determined by the comparison rules and the upper or lower limit. Measurement direction and measurement speed are determined by the metrologist, which will generate different measurement values.
2. Difference between the filtration operations of specification and verification. The difference in implementation of a filter is the main factor in the filtration operation. For example, if a Gaussian filter is specified in the specification, in the implementation of the verification process, there are different kinds of algorithms that can be utilised i.e. convolution algorithms [9,10], fast and reliable convolution algorithms [11], Fourier transform based algorithms [12] and approximation algorithms [13]. The differences from those algorithms are one of the sources of method uncertainty.
3. Difference between the evaluation operations of specification and verification. In surface texture, the evaluation operation is the calculation procedure of the specified parameter value. Different instruments may have differences interpretation of the calculation of a parameter. For example, the definition of parameter *Ra* in ISO 4287 of $Ra = \frac{1}{l}\int_0^l |Z(x)|dx$ is a continuous model, but in implementation, PTB and NIST use a discrete model, and whereas NPL use a continuous model based on interpolation between discrete points.

The implementation uncertainty defined in ISO/TS 17450-2:2012 is the narrow definition of traditional measurement uncertainty. The evaluation of method uncertainty assumes the implementation uncertainty is zero. But even if the implementation uncertainty is zero, it is impossible to reduce the measuring uncertainty below the method uncertainty. To reach a low measurement uncertainty it is not only necessary to have accurate instruments, a good environment, a trained operator, etc, it is also necessary that the measuring process measures what the specification requires. A method is needed to generate a series of detailed verification parameters according to the specification and guarantee the measuring process measures exactly what the specification requires thus reducing the method uncertainty.

3. The discussion of possible evaluation methods of the uncertainties

A lesson to learn from the last section is that as far as cost is concerned, if the metrologist invests in the ability to measure a workpiece with low measurement uncertainty while specification uncertainty is high, then the design cost may be low with high measurement costs while the total cost may increase and the total uncertainty is still high. If designers create a specification with low specification uncertainty then measurement uncertainty will also be decreased. In this case the design cost may be high but measurement cost will be low while the total cost may not change and the total uncertainty will be lower. This is because a complete specification can give inspector detailed information about how to measure the component, so the method uncertainty and related measurement uncertainty will decrease. Hereby, the latter can give us clear information - the control of specification uncertainty is able to distribute the product resource in a more effective and economical way. To this end, possible evaluation methods for the specification uncertainty of surface texture will be investigated in this section.

3.1 Analysis of specification uncertainty in surface texture

The ten control elements of surface texture in Fig. 3 can be expressed as E_1, E_2, $E_3 \ldots E_{10}$ respectively. These elements can be divided into two groups according to the effect on the measured value and measurement result, see Fig. 5. One type which includes E_2-E_5 and E_8-E_{10}, has direct impact on the measurement value, thus influencing the measurement results. Each type of element has a different number of options. Different selections of element E_4 (parameter) will lead to large difference of measurement values according to the different definition of parameters. The parameter values will diverge with different features such as roughness, waviness and primary profile, for example, the difference between *Ra*, *Wa* and *Pa* for a ground profile can be 0.4818μm, 0.1008 μm and 0.5007 μm respectively. In addition, a clear specified element E_9 could prevent different measurement directions. Another type, which includes elements E_1, E_6 and E_7, has no effect on the measured value, but has a direct impact on the measurement results.

For an incomplete specification, one option must be selected from each control element to combine a complete specification. For example, a specified specification with elements $E_{8\text{-}3}$, E_4, E_7 and E_{10} is shown in Fig. 6, the combination of incomplete elements E_1, E_2, E_3, E_5, E_6 and E_9 will be C_2^1, C_{13}^1, C_5^1, C_6^1, C_2^1 and C_7^1 respectively. Then, the total of combination will be

$$C_2^1 \times C_{13}^1 \times C_5^1 \times C_6^1 \times C_2^1 \times C_7^1 = 10920.$$

This means that there are 10920 different specification combinations in order to complete the specification. However, there are a great many combinations which cannot be corrected such as combination1, 2, 5 and 6, because the relationships between the control elements in these complement combinations are incorrect. For instance, the surface texture lay cannot be $E_{9\text{-}1}$ (⊥) but $E_{9\text{-}5}$ (M) as the manufacturing process is sanding casting, and the transmission band should not be $E_{3\text{-}1}$ (0.0025-0.08) but $E_{3\text{-}5}$ (0.008-0.25) because the parameter value is 3.2μm. Therefore, metrologists should understand the relationships between different control elements to make a correct interpretation for an incomplete specification. After the relationship clarification, as E_{10} has only one E_9 option, the combination of E_9 will be C_1^1 and can be omitted. The correct combination then will be elements E_1, E_2, E_3, E_5 and E_6 with a combination

$$C_2^1 \times C_{13}^1 \times C_5^1 \times C_6^1 \times C_2^1 = 1560.$$

Considering the cost, the default values of E_2 and E_5 of $E_{2\text{-}1}$ and $E_{5\text{-}3}$ are respectively applied. Then it is possible to reduce the combination to

$$C_2^1 \times C_5^1 \times C_2^1 = 20.$$

However, as this is an incomplete specification, both correct and incorrect complements lead to different measurement values. The dispersion of these values is the specification uncertainty. Although there are eight elements contributing to the different measurement value, major elements influencing the measurement value are the parameter E_4. Because of the different definition of parameters, for the same profile data, the difference in values between parameter *Ra* and *RSm* can be extremely high. In an example of a profile produced by milling, the *Ra* value is 0.6μm and *RSm* is 193μm, the difference between these values is a factor of 321. The specification uncertainty can be reduced greatly if the designer understands the relationships between different control elements and then makes a correct and complete specification.

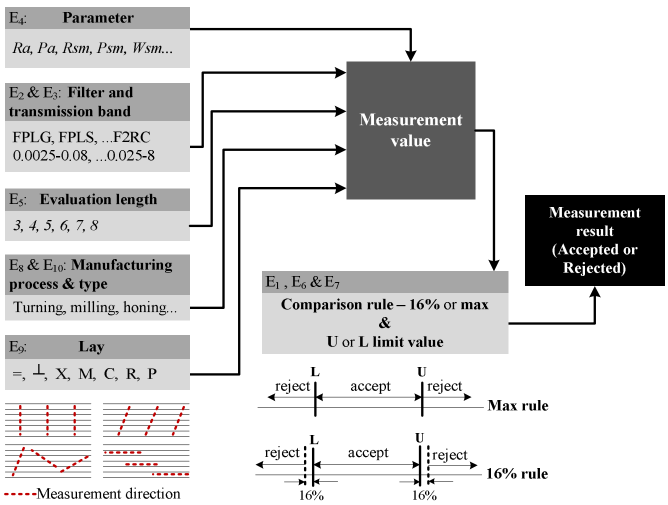


Fig. 5. Different elements contribute to the specification uncertainty in surface texture

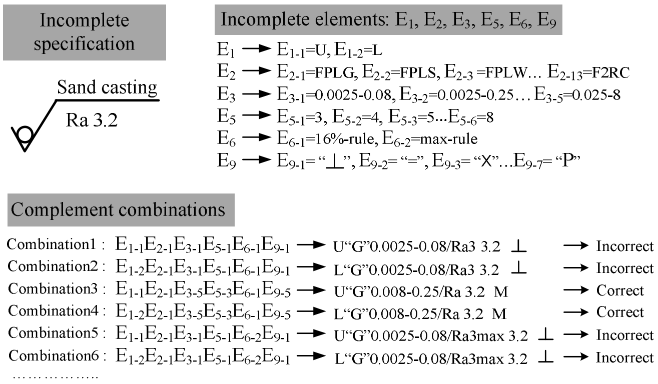


Fig. 6 An example of incomplete specification and related complement combinations

3.2 Management and evaluation of specification uncertainty in surface texture based on case study

A universal formalization approach of the specification uncertainty for surface texture is not always practical. An exhaustive analysis should be applied before an evaluation approach is employed. As shown in the Fig. 7, the management of specification uncertainty for surface texture could be operated as following steps:

Step 1: Analyse all incomplete specification elements;

Step 2: After relationship restriction process, omit all the restricted and default elements; Add a relationship process flow chart here.

Step 3: Combinations of remain elements;

Step 4: Collect the measurement value and results for different combination;

Step 5: Analyse the deviation of the different results, evaluate the specification uncertainty for the incomplete specification.

Using the incomplete specification example indicated in Fig. 6, an evaluation method to estimate specification uncertainty is established in this section. According to the flow chart of management, step 1- 3 is carried out firstly. There are 20 different complete combinations, and 16 sets of related measurement were carried out. 12 or 3 random measurements (depended upon the comparison rule E_6 is "16%" or "max-rule") for each set under the same conditions were carried out. The average and deviation of the 12/3 measurement values for the 16 sets are listed in table 1, where 1 and 0 in the measurement result column represent accepted and rejected respectively.

The specification uncertainty u_s is the dispersion of 16 sets of measurement value. The standard deviation of the 16 set of average measurement value is used to represent the dispersion:

$$u_s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{N}(X_i - \overline{X})^2} \quad (n=16)$$

Here, the average of $\overline{X}$ = 1.9916, and u_s is

$$u_s = \sqrt{\frac{1}{16-1}\sum_{i=1}^{N}(X_i - 1.9916)^2} = 0.4953$$

The probabilities of 16 sets of measurement being rejected and accepted are 50% and 50% respectively, according to the table 1. The specification uncertainty derived from measurement results is 50%, and the one derived from measurement value is 0.4953 which is 15.5% of the limit value. In this case, if only considering measurement value, specification uncertainty of 15.5% is acceptable, however, when the measurement result is taken into account, 50% specification uncertainty is too large to be accepted. It is the measurement result is essential features in the measurement and also for the whole product process, clear defined control element E_1 is the most key features for providing a precise measurement result.

4. Conclusions

The discussion of uncertainties in surface texture concludes that the control of specification uncertainty can distribute the product resource in a more effective and economical way. A comprehensive analysis of specification uncertainty, therefore, is implemented. The result of a statistical evaluation of the specification uncertainty reveals the importance of reducing the specification uncertainty derives from the measurement result, but not only measurement values.

REFERENCES

1. JCGM 100:2008, "Evaluation of measurement data – Guide to the expression of uncertainty in measurement", JCGM 2008
2. JCGM 101:2008, "Evaluation of measurement data –Supplement 1 to the 'Guide to the expression of uncertainty in measurement' – Propagation of distributions using a Monte Carlo method", JCGM 2008
3. Bennich, P., "Geometrical measurements", MetroTrade Workshop - Traceability and Measurement Uncertainty in Testing, Berlin, 2003
4. Whitehouse, D.J, Jiang, X., "General Metrology in Manufacture", in 12th CIRP Conference on Computer Aided Tolerancing, CIRP: Huddersfield, UK, 2012
5. Dantan, J.Y., et al., "Correlation uncertainty-Application to gear conformity", CIRP Annal - Manufacturing Technology, Vol. 59, No.1, pp.509-512, 2010
6. Whitehouse, D.J., "Function maps and the role of surfaces", International Journal of Machine Tools and Manufacture, Vol. 41, No. 13, pp.1847-1861, 2001
7. Nielsen, H., "How long is a piece of string? - Some overlooked considerations for uncertainty estimation", http://www.hn-metrology.com/string.pdf
8. Scott, P. J., "The case of surface texture parameter RSm". Mea. Sci. Technol., Vol. 17, No.3, pp.559-564,2006
9. Raja, J. and Radhakrishnan, V., "Digital filtering of surface profiles", Wear, Vol. 57, pp.147-155, 1979
10. Whitehouse, D.J., "Improved type of wavefilter for use in surface-finish measurement", Proc Inst Mech Eng, Vol. 182, pp. 306-318, 1967-68
11. Krystek, M., A fast algorithm for roughness measurement. Precision Engineering, Vol. 19, pp. 198-200, 1996
12. Raja, J. and Radhakrishnan, V., Filtering of surface profiles using fast Fourier transform. Int. J. Mach. Toll Des. Res, Vol. 19, pp. 133-141, 1979
13. Yuan, Y. B., A fast algorithm for determining the Gaussian filtered mean line in surface metrology. Precision Engineering, Vol. 24, pp. 62-69, 2000

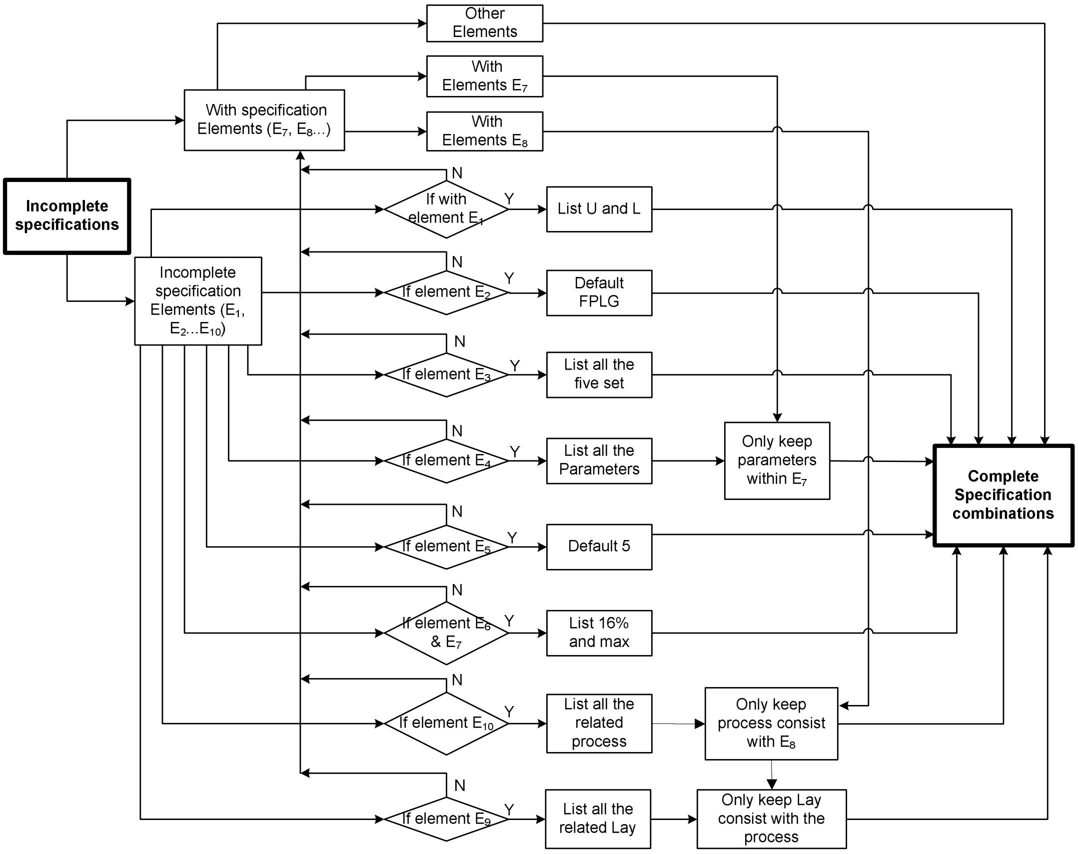


Fig.7 The flow chart of the management of specification uncertainty

Table 1 Measurement value and result for Case 1

Combination No.	*Elements combinations*	*Specifications*	*Measurement value*		*Measurement result (1or 0)*
			Average	*Deviation*	
1	E_{1-1} E_{3-1} E_{6-1}	U"G"0.0025-0.08/Ra 3.2 ⊥	1.2568	0.2389	1
2	E_{1-1} E_{3-2} E_{6-1}	U"G" 0.0025-0.25/Ra 3.2 ⊥	1.9767	0.251	1
3	E_{1-1} E_{3-3} E_{6-1}	U"G"0.0025-0.8/Ra 3.2 ⊥	2.3171	0.184	1
4	E_{1-1} E_{3-4} E_{6-1}	U"G"0.008-2.5/Ra 3.2 ⊥	2.3356	0.0746	1
5	E_{1-1} E_{3-5} E_{6-1}	U"G"0.025-8/Ra 3.2 ⊥	N/A	N/A	N/A
6	E_{1-2} E_{3-1} E_{6-1}	L"G"0.0025-0.08/Ra 3.2 ⊥	1.088	0.3119	0
7	E_{1-2} E_{3-2} E_{6-1}	L"G"0.0025-0.25/Ra 3.2 ⊥	2.0523	0.2879	0
8	E_{1-2} E_{3-3} E_{6-1}	L"G" 0.0025-0.8/Ra 3.2 ⊥	2.4231	0.2051	0
9	E_{1-2} E_{3-4} E_{6-1}	L"G"0.008-2.5/Ra 3.2 ⊥	2.2985	0.13	0
10	E_{1-2} E_{3-5} E_{6-1}	L"G"0.025-8/Ra 3.2 ⊥	N/A	N/A	N/A
11	E_{1-2} E_{3-5} E_{6-2}	L"G"0.025-8/Ra max 3.2 ⊥	N/A	N/A	N/A
12	E_{1-1} E_{3-1} E_{6-2}	U"G"0.0025-0.08/Ra max 3.2 ⊥	1.1993	0.2083	1
13	E_{1-1} E_{3-2} E_{6-2}	U"G" 0.0025-0.25/Ra max 3.2 ⊥	2.1852	0.0405	1
14	E_{1-1} E_{3-3} E_{6-2}	U"G"0.0025-0.8/Ra max 3.2 ⊥	2.2204	0.1726	1
15	E_{1-1} E_{3-4} E_{6-2}	U"G"0.008-2.5/Ra max 3.2 ⊥	2.398	0.0221	1
16	E_{1-1} E_{3-5} E_{6-2}	U"G"0.025-8/Ra max 3.2 ⊥	N/A	N/A	N/A
17	E_{1-2} E_{3-1} E_{6-2}	L"G"0.0025-0.08/Ra max 3.2 ⊥	1.2233	0.1313	0
18	E_{1-2} E_{3-2} E_{6-2}	L"G"0.0025-0.25/Ra max 3.2 ⊥	2.1097	0.0863	0
19	E_{1-2} E_{3-3} E_{6-2}	L"G" 0.0025-0.8/Ra max 3.2 ⊥	2.4587	0.0733	0
20	E_{1-2} E_{3-4} E_{6-2}	L"G"0.008-2.5/Ra max 3.2 ⊥	2.3234	0.061	0