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Dimensioning and tolerancing of coated parts

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S u m m a r y . One of the most important problem in process planning for manufacturing of coated parts is the selection of the optimal relationship between the requirements for precision shaping of blanks for coating deposition and finally coated part. The processes of coatings machining differs from the machining processes of monolithic materials. One of the reasons of low workability of some coatings, especially wear-resistant, is a consequence of strong abrasivity coatings which contain hard particles. Therefore, establishment of rational dimensional tolerances in manufacturing operations is important and has a significant impact on the quality of the technological processes and the cost of manufacturing parts. This paper provides an integrated methodology for geometric dimensioning and tolerancing in manufacturing of coated parts.

K e y w o r d s : allowance, coating, geometric dimensioning, tolerance analysis.

INTRODUCTION

In the problem of machinery quality control is of great importance to establish its optimal level at which the difference between the savings in consumption and cost of development and manufacturing of products will be maximized. For solving this problem an important role playing the application of protective and functional coatings and surface modification of machine parts and production tools to facilitate resources and energy savings in the manufacturing and long-term performance of machines. Coatings and surface modification technologies allow the engineer to improve the performance, extend the life, and enhance the appearance of materials used for engineering components. These technologies have been developed because the interactions of manufactured components with other components, liquid, and/or gaseous environments can result in component degradation and failure. Additionally, coating technologies enhance the performance of components by selectively applying coatings that perform specific tasks without compromising the benefits of the substrate material [2-4,27].

Coatings are no longer limited to the traditional applications associated with wear and corrosion [9,13,14]. The use of coatings for decorative effects, implant prostheses, and electrical isolation/conduction is increasing daily. As the technological needs of a society become more complex, the implementation of surface modification and coatings will assume an increasing role in meeting those needs.

Coatings often are treated after deposition to establish final dimensions or to improve or change the coating microstructure, thus avoiding some or all of the shortcomings of deposited coatings. Methods used to obtain these results include chemical/physical treatments, thermal treatments, and mechanical treatments, including machining, grinding, shot peening, hot isostatic pressing, and polishing [3,15,19,21].

In the process of repairing, the worn surface is usually coated with the layer, which thickness exceeds magnitude of wear. After the surface is coated it is machined by one of the available methods [20,21].

Preproduction planning is a fairly complex set of design and calculation work. Development of process plan (PP) involves the selection the most appropriate manufacturing processes and the order in which they should be performed to produce a given part specified by design engineer. The process sequence should be the production method that satisfies all of the design and quality requirements and also achieves the lowest possible product cost. The common goal of process planning is the creation of an optimal PP on any (mostly economic) optimality criterion. But none of the possible PP can not be considered absolutely optimal, as always there is a possibility to improve it according to the accepted criteria of optimality [17]. In process planning of coated parts there are the specific requirements that must be satisfied by PP: 1) the quality of functional coating should be stable for a long time. The process can prevent the risk of obtaining of some parts with deviations of coating thickness as its other parameters from the specified by part drawing. For some parts it is important to control not only final surface dimensions but simultaneously the specified value of coating thickness with specified tolerance limits, 2) in some cases can be specified special objectives for surface processing before coating deposition, which define surface integrity, for example, residual stresses in subsurface layer, hardness variations, etc. There are the various types of surface and subsurface alterations that are attributable to the different forms of energy applied in processing of work-piece. There may be metallurgical or other changes in the material immediately beneath the surface that can have a significant effect on part mechanical properties, coating bond strength and others.

LITERATURE REVIEW

Tolerance assignment is fundamental for successful mechanical assembly, conformance with functional requirements and component interchangeability, since manufacturing with perfect geometry is virtually unrealistic. In engineering drawings Geometric Dimensioning and Tolerancing (GD&T) correlates size, form, orientation and location of the geometric elements of the design model with the design intent, therefore it has a profound impact on the manufacturability, ease of assembly, performance and ultimate cost of the component [12,16]. High geometrical and dimensional accuracy leads to high quality, however, tight tolerances lead to an exponential increase of the manufacturing cost. Though the importance of tolerance design is well understood in the engineering community it still remains an engineering task that largely depends on experimental data, industrial databases and guidelines, past experience and individual expertise [23,24].

Geometrical and dimensional tolerances are of particular importance, on the other hand, not only in industrial production but also in product development, equipment upgrading and maintenance. The last three activities include, inevitably, RE tasks which go along with the reconstruction of an object CAD model from measured data and have to do with the assignment of dimensional and geometrical manufacturing tolerances to this object. In that context, tolerancing of RE components address a wide range of industrial applications and real-world manufacturing problems such as tolerance allocation in terms of the actual functionality of a prototype assembly, mapping of component experimental design modifications, spare part tolerancing for machines that are out of production or need improvements and no drawings are available, damage repair, engineering maintenance etc.

Process planning for parts involves the large complex of works and related details and required decisions making. The selection of operational dimensions, allowances, tolerances of work part, as well as evaluation of the accuracy of TP as a whole is one of the key task in part design and process planning as it affects both the product's functional requirements and manufacturing cost [17]. Traditionally, this important phase of product development is accomplished intuitively to satisfy design constraints, based on handbooks' data and /or skill and experience of the designers. Tolerance design carried out in this manner does not necessarily lead to an optimum design. The dimensional analysis of process plan for coated part manufacturing has three varieties: 1) analysis of newly designed PP when only drawing of coated part is available, route and operational sheets and documentation are not available, 2) analysis of newly designed PP when drawing of coated part, route sheet and drawing of work part, partially treated before coating deposition are available. This is typical situation when using concurrent engineering, and 3) analysis of the current PP which not provide required parameters for quality, consumption of materials and other resources and total part costs. In such cases it is necessary to reveal the dimensional links of machining operations before coating deposition, coating deposition process and subsequent finishing operations, and then by solving of dimensional chains and to find actual value of allowances disposed of in all stages of the processing of the coated surface and determine possible ways for improving of PP of coated part. Dimensional analysis enables to accomplish the following objectives: 1) to establish science-based operating sizes and technical requirements for all stages and operations and the manufacture of coated parts, which would require the minimum of PP correction, and 2) to establish the design of rational dimensions of workpieces with the minimum necessary allowances for processing of the workpiece to be coated and dimensioning of finishing coating operations.

Understanding the causes and effects of dimensional and geometric variations is a major concern in the design and manufacture of mechanical products [7]. However, effective tools for assisting designers in allocating tolerances and identifying trade-offs during the design process do not exist today.

CAD models, as one of the key inputs of many automated manufacturing and production systems, should include all the relevant and essential information on each and every feature of the component so it can be manufactured [11]. For instance, a particular part working surface surface feature in a CAD model can be manufactured once the coating type, position, diameter, thickness, surface finish requirement, including the tolerance on all of the parameters and constraints are known. It is understood that the initial dimension placed on the features in any drawing or CAD model should be the exact dimension that would be used if it was possible to work without tolerances. However, the tolerancing is required to make the part cost effective and feasible to manufacture. In the case of sensitive parts or features, the tolerance should be defined in more detail including geometrical features such as waviness, cylindricity, perpendicularity.

The accuracy cost of a part dimension depends on the process and resources required for the production of this dimension within its tolerance limits. This cost is thus primarily determined by the part material, geometry and tolerances. Given the material, geometrical part characteristics such as shape, size, shape complexity, existence of internal surfaces and feature details has a direct impact on the accuracy cost as they are taken into consideration for the process planning and the required machines and tools [22]. In a concurrent design environment, a robust optimum method is presented to directly determine the process tolerances from multiple correlated critical tolerances in an assembly.

Etienne et.al. deals with tolerance allocation driven by an activity based approach. Its main objective is to rationally give a good indicator of the relevance of tolerances values fixed by designers [8].

The majority of the published articles on tolerance synthesis are based on optimization, most of which use the cost-tolerance models

Tolerance modelling involves the modelling of the relationship between the tolerance information associated with part features and their effect on assembly functionality. The relationship captured by the tolerance model is referred to as the assembly response function [18].

Quality control (QC) plan is an important component of manufacturing planning for mass customization [26]. QC planning is to determine the operational tolerances and the way to control process variation for assuring the production quality against design tolerances. It includes four phases, i.e., tolerance stack-up analysis, tolerance assignment, in-process inspection design, and the procedure of error source diagnosis & process control. Based on the tolerance stack-up model and process capability analysis, a tolerance assignment method is developed to determine the operation tolerance specifications in each setup.

In conclusion, we note that the available literature does not address the definition of the dimensions and tolerances for surface preparation before coating deposition. The objective of this paper is to analyze the dimensional relationships between the three main stages of the manufacture of coated parts, and, namely, surface preparation for coating deposition, coating deposition and subsequent dimensional processing of the coating.

DIMENSIONAL TOLERANCING OF COATED PARTS

Tolerance analysis is a key element in industry for improving product quality and decreasing the manufacturing cost. In addition, it participates to an eco-aware attitude since it allows industrials to manage and reduce scrap in production. Tolerance analysis concerns the verification of the value of functional requirements after tolerance has been specified on each component [6].

Dimensional tolerances are required to be sensibly defined and presented in a way to guarantee the functionality of the part while minimising the manufacturing cost. In reverse engineering the design information including the overall geometry, surface finish and dimensional tolerances is extracted from scanning and analysing the existing part [11]. However the tolerance accommodation is one of the challenging problems that is conventionally dealt with by design initiatives of the reverse engineering expert in a rather “redesigning” approach. In this work the existing information from the part machining and surface finish measurement result is used to estimate the surface finish and dimensional tolerance information. This method can be integrated into a reverse engineering system for further automation and user flexibility. A wear factor can be added in the tolerance approximation process in the further development of the system, by involving a correction ratio to the initial estimation. Assembly analysis can also be included to better estimate the dimensional and surface tolerances for higher sensitivity components.

Campatelli introduces a new approach based on Axiomatic Design to simplify the process of Tolerance Synthesis. The main advantage of this approach is that all of the information needed for the Tolerance Synthesis is easily included in the classical AD framework [5]. The information that must be stored in the design matrices is mainly related to the production cost vs. tolerance curves and the tolerance chain needed for the synthesis phase.

In some cases of real manufacturing of coated parts the calculation of dimension chains can have the certain singularities. For example, the typical case is operation of coating finishing with removal of preselected coating allowances. It takes place in manufacturing of parts with wide dimensional tolerances of the coated surface and stringent requirements for the surface texture and therefore it is necessary to use finishing operations as superfinishing, honing, lapping, polishing, etc. In such cases the value of removed coating layer is regulated and for the calculation of technological dimensions it is possible to take allowance for coating processing as chain link, and the final dimension of coated surface as the closing dimension of dimension chain.

Assignment of rational dimensional tolerances for manufacturing operations is very important and has a significant impact on the quality of the PP and on the cost of part manufacturing. The extension of design tolerances is promoted to reduction of cost of processing operations. The wider tolerances enable performing operations at higher operational parameters, decrease time to set up the machine, less frequent corrective maintenance of machinery, etc. However, the expansion of tolerances on any operation increases the average allowances and, as a consequence, in the general case is promoted to increase the dimensions of the workpiece and its cost. In the manufacturing of coated parts increasing the tolerances on the surfaces to be coated results on an increase of the required thickness of the coating and on increase of allowance for the coating processing. In most cases, protective and functional coatings are characterized by a poor workability [15,21], which is consequence of their specific properties: high brittleness, nonuniform hardness, inhomogeneous chemical composition over the cross section, a large number of components of the microstructure (carbides, borides, and other intermetallic components with a high hardness) , substantially porous structures, etc. Therefore, the machining of coatings differs from the machining of monolithic materials. Low workability coatings is also a consequence of their large abrading ability because they contain hard particles.

Besides, the excessive coating thickness is an additional source of them internal tensile stresses have a negative impact on the bond strength and performance of the coatings.

Selection of tolerances and ISO accuracy degrees in design of machine parts traditionally are based on the principles of ensuring the operational and structural requirements for parts and assembly machine as a whole. Moreover, in some cases for improvement of reliability, durability and accuracy of machines designers tend to approximate the dimensions of parts to their calculated values of nominal dimensions. However, these design requirements are limited by technological capabilities and possibilities of technical measurements. In most cases this leads to increased complexity and cost of manufacturing and part control. For the processing of parts for more high accuracy requires increasing labor and material costs for equipment, fixtures, tools and control. The decreasing of tolerances results on increase of the probability of rejects. Relative cost of part manufacturing in these cases is decreasing when the tolerance increases by hyperbole, that is $C\delta$ = const, where C - cost of surface processing, δ - tolerance of the surface dimension.

The making of functional part surfaces with higher accuracy provides high precision couplings and permanence of their character in the large lots and their higher operational performance in general. Manufacturing of parts with extended tolerances are easier and does not require precise finishing equipment and technological operations, but reduces the accuracy, and hence the reliability of the machines. This contradiction between the operational requirements and technological capabilities is solved on the basis of technical and economic calculations based primarily of operational requirements. Application of protective and functional coatings on mating parts complicates the problem of selecting the optimum tolerances and allowances for processing operations. In this case it is necessary to consider three main process steps: surface preparation prior to coating deposition, coating deposition, and, coating processing.

Before coating deposition surfaces need to be shaped in order to meet their dimensional specifications. Some base material has to be removed in the places where the coating is to be deposited. Therefore it is necessary to develop and apply the principles of rational choice surface tolerances of parts prepared for coating deposition. Linear operating dimensions of parts subjected to thermal spraying or other methods of coating deposition must be chosen from the condition not only provide the desired thickness of the coating, but the minimum cost of its preparation and post-deposition dimensional processing. We assume that given on the part drawing the coating thickness on the given surface of the finished part is the original dimension of the drawing with a relatively small tolerances. However, in many cases, the tolerance of coatings thickness currently in the drawings are often not specified. Deposition of the coating effect on change of part shape and dimensions of it surfaces. The desired coating thickness in the drawing is provided not directly but indirectly via the machining dimensions. So promising is the use of technological dimensional chains that need to be solved to determine the linear operating size machining and coating thickness and which have a close parallel communication [1,10].

The solving of system of dimensional chains can simultaneously accomplish two conditions: remove the asperities and defective layer on the coating surface and achieve a desired thickness of the applied coating accordance with finished part drawing. The first condition is satisfied when choosing the value of the minimum allowance $Z_{on}^{\min}$ for equations given in [1,10], the second – the choice of tolerances on components of the chain links on the equation:

$$\sum_{m+n} \delta_i \le \delta_k ,$$

where: m – the number of enlarging chain links, n – the number of diminishing chain links of dimensional chain, δ_k – coating thickness tolerance of the finished part.

COST - EFFECTIVE TOLERANCE ASSIGNMENT

The matter of selection of the minimum allowance for coating processing is very essential requirement to process plan of coated parts. From the geometrical point of view it may seem that the absolute value of the thickness of removed coating layer during finishing operation is not important, and it is necessary mainly to secure coating thickness fluctuation after finishing operations within specified by part drawing. Also from this point of view there are two equivalent alternatives of proportion between thickness of deposited coating and allowance for this coating finishing. For example, first variant is thickness of deposited coating as t_{dep} = 0,5…0,6 mm and finishing allowance $Z_{fin}^{\min}$ = 0,2 mm, and for other variant t_{dep} = 0,8…0,9 mm and $Z_{fin}^{\min}$ = 0,5 mm. However, from the technical and economic points of view these options completely are ambiguous. First of all, increase of deposited coating thickness results on sharp rising of adverse internal stress reducing bonding strength between coating and substrate, which sometimes cause cracking and detaching of coatings. In this regard, it is necessary to strive for the smallest possible thickness values of deposited coatings. Furthermore, for many types of coating, for example, obtained by surfacing, their properties (hardness, structure, residual stresses, etc.) are changing in direction from outer surface to the bottom surface. Therefore, in such cases it is necessary to strive for the smallest possible values of allowances $Z_{fin}^{\min}$. For this purpose, it is necessary that for the processes of coating deposition and finishing processing were preceded by such pretreatment methods in which minimum values by the constituent elements of the allowances are provided. Practically, this problem can be solved by applying a surface processing before coating deposition with an accuracy greater than the accuracy required of the coated surface of the finished part accordance with the part drawing.

The reduction of the thickness of deposited layer and allowances for finishing processing of coatings is advisable from the economic point of view. Even a slight increase of the thickness of the deposited layer requires the increase of consumption of expensive coating material and operational time of coating deposition and, hence, the appropriate cost of the coating obtaining. In addition, usually coatings have poor machinability, which results on increase of cost of coating dimensional processing.

Furthermore, there is a need for careful approach to the selection processes of coating deposition based on accounting of design features and details of the technological features of the coating. Insufficiently rigid parts should be coated by processes with the lowest possible heat input to avoid warping and other geometrical distortions of form and dimensions of the coated part.

Comparison and selection of more suitable process plan (PP) for manufacturing of coated part is necessary to execute by whereas accuracy of PP, which has a significant impact on material consumption rate for coating obtaining:

$$H_{cm} = S_c \left(t_{\min} + \delta_w^{\pm} + Z_{fin}^{\min} + 0,5\delta_c\right)\times$$
$$\times\rho_c \left(1 - P/100\right)\eta_{dep}\eta_p,$$

where: S_c – coating surface area, $t_{\min}$ – minimum required coating thickness on the finished part, $\delta_w^{\pm}$ – tolerance of surface dimension after preparation for coating deposition, $Z_{fin}^{\min}$ – the minimum allowance for processing of deposited coating, δ_c – tolerance of deposited coating thickness, ρ_c – the density of the coating material, P – porosity of the coating, η_{dep} – utilization of coating material associated with its loss during the deposition process, η_p – the same associated with the kinematics of the deposition process and part geometry.

As it is known, that the tolerance for any ISO accuracy degree:

$$\delta = ia,$$

where: i – unit of allowance, a – a factor equal to the number of units of tolerance.

In the ISO system unit of tolerance is [25]:

$$i = 0,45\sqrt[3]{d_{av}} + 0,001d_{av},$$

where: d_{av} – average dimension for a given range of dimensions.

The allowance unit i, reflecting the influence of technology, part design and metrological factors, expresses the dependence of the tolerance for the nominal value of the dimension is a measure of precision. It allows the development of tolerance system for a wide range of design parameter values. To normalize levels of accuracy classes (degrees) it is assigned degrees of accuracy of manufacturing. For each class (degree) of accuracy exists naturally built a number of fields tolerances in which different sizes of similar dimensions surfaces of the parts have the same relative accuracy, defined roughly the same value of the coefficient a. In an ISO number of units tolerance when switching from one to another quality class accuracy ranging from 5th varies approximately exponentially (for example, 7, 10, 16, 25, 40, 64, etc.) with common ratio $\sqrt[3]{10} \approx 1,6$.

Analysis of dependence of tolerances from the magnitude of the dimension for the main accuracy degrees shows that with the dimension increase and decrease the accuracy requirements of their performance, the tolerance can approach or even exceed the thickness of some deposited coatings. In these cases it is necessary to increase of deposited coating thickness to achieve the desired value of allowance for finishing operations.

The coating thickness is usually a function parameter which specifies the availability of coated part. The ratio of coating thickness t to the allowable amount of wear should be greater than 1. Since the thickness of the coating is usually much less than the nominal dimension of the surface ($t << d$), the tolerance on the value of the unit thickness of the coating will be much less than the tolerance values for the units of the dimensions of finished coated part and the workpiece which prepared for coating deposition:

$$i_c << i_p; i_c << i_{wp},$$

because the dimensions of part and workpiece are belong to various dimension ranges.

From the theory of dimensional chains it is follow that tolerance of coating thickness is equal to the sum of tolerances for dimensions of the workpiece to be coated δ_{wp} and after coating deposition δ_{cp}:

$$\delta_c = \delta_{cp} + \delta_{wp}.$$

From the definition of tolerance value for a certain ISO accuracy degree the last expression can be written as:

$$\delta_c = i_{p(wp)}(a_p + a_{wp}) = i_c a_c .$$

It is assumed here that $i_p = i_{wp}$, as they, as a rule, from the same dimension range. In case of surfacing of thick layers it is possible that $i_p \neq i_{wp}$. Then:

$$\delta_c = i_p a_p + i_{wp} a_{wp} .$$

For thin films or coatings, for example, obtained by methods of thermal spraying, will be used the first expression.

In view of the relative smallness of the coating thickness it is possible to neglect by value of 0,001d_{cav}. Then we can write:

$$a_c = \frac{i_{p(wp)}}{i_c}(a_p + a_{wp}) = \\ = \left(\sqrt[3]{\frac{d_{wpav}}{t_{cav}}} + \frac{0,001}{0,45}\frac{d_{wpav}}{\sqrt[3]{t_{cav}}} \right)\left(a_p + a_{wp}\right).$$

As the thickness of coatings usually is included in the dimension range of up to 3 mm as the dimensions of surfaces of machine elements to be coated are predominantly in the dimension range above 18 mm (d_{wpav} = 24, 40, 65, 100 mm, etc.), the ratio $i_{p(wp)}$ / i_c is typically of the order of 3 or more. Therefore, the number of ISO accuracy degrees for tolerance of the coating thickness is many times higher than the corresponding number for the dimensions of the part and the workpiece to be coated, and therefore accuracy of thickness of dimensionally treated coating below compared to the surface dimension for several ISO accuracy degrees. As it is known, the number of units in ISO during the transition from one degree to another varies approximately in a geometric progression with ratio 1,6.

With the increase of the relative value of the allowance for coating processing increases the relative cost of dimensional processing of coatings is growing. One of the ways of reducing the allowance value for finishing of coatings is the reduction of dimension tolerance of the workpiece before coating deposition. Therefore, it is recommended to prepare surfaces for coating deposition with accuracy of average ISO accuracy degree with conditions of compliance of required tolerance values throughout the dimension range of surfaces with coatings.

It is possible to determine the average ISO accuracy degree by computational-graphical manner using the graphic dependencies or calculation formula:

$$JT_{av} = JT_a + (ab / ac),$$

where: JT_a – nearest ISO accuracy degree, having a value of tolerance for a given dimension is below than predetermined, *ab* – the difference between the value of a given (received) tolerance and tolerance for ISO accuracy degree, *ac* – the difference between the values of the nearest less precise degree and given degree JT_a.

CONCLUSION

1. The technology of the manufacturing of coated parts is the integration of traditional manufacturing technology and various engineering technologies for coatings deposition as surfacing and related welding processes, powder metallurgy, electroplating, thermal spraying, PVD and CVD, etc.). This is unique trend providing production of high quality and cost-engineering patrs, which could not be developing successfully without analysis of the accuracy of coated parts, including the stages of surface preparation and coating deposition.

2. For more wide adoption of coatings technology and other methods of surface engineering it is extremely necessary to develop standards for the accuracy parameters of coated parts and processes for coating deposition.

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ОПРЕДЕЛЕНИЕ РАЗМЕРОВ И ДОПУСКОВ ДЕТАЛЕЙ С ПОКРЫТИЯМИ

Юрий Харламов, Али Аднан Мансур Ал-Джавахери

А н н о т а ц и я . Одной из самых важных и трудных проблем в разработке технологических процессов изготовления деталей с покрытием является выбор оптимального соотношения между требованиями к точности формирования заготовок под нанесение покрытий и окончательно обработанной детали с покрытием. Процессы обработки покрытий резанием отличаются от процессов обработки традиционных материалов. Одной из причин низкой обрабатываемости некоторых покрытий, особенно износостойких, является сильная абразивность покрытий, которые содержат твердые частицы. Таким образом, установление рациональных допусков размеров на операциях изготовления деталей с покрытиями является важным и оказывает значительное влияние на качество технологических процессов и стоимости изготовления детали. В данной статья представлена интегрированная методика определения геометрических размеров и допусков на межоперационные размеры изделий с покрытиями.

К л ю ч е в ы е с л о в а . Припуск, покрытие, определение геометрических размеров, анализ допусков.