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APPLICATION OF QUALITY ENGINEERING CONCEPTS IN OPTIMIZING DIAMOND GRINDING PROCESS FOR HARD METAL CUTTING TOOLS USING RESPONSE SURFACE METHODOLOGY

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Abstract: This paper presents an investigation on the optimization and the effect of diamond grinding parameters on the cutting tool's such quality characteristic which is usually considered for tool quality by a customer. This characteristic considers tool life and reliability of the ground tool and, consequently, evaluates the total technological cost which includes specific tool grinding cost as well as the cost of subsequent machining operation perform by that tool. For this purpose, by keeping in sight Taguchi's quality engineering philosophy, a plan of experiments based on response surface methodology was designed. Diamond grinding wheel, a suitable in-process dressing method and hard metal tool insert as workpiece material were used in experiments. The workpiece was ground under the different settings of grinding speed and cross feed on a Universal tool & cutter grinder, model 3D642E (Russian made). The results showed that grinding speed and cross feed were the dominant variables on the above mentioned quality characteristic. The smaller values of grinding process input parameters were found to be suitable for enhanced tool life. Experimental results are discussed through two response surface plots.

Key words: tool quality, diamond grinding process

1. INTRODUCTION

Diamond grinding, i.e. grinding with diamond wheels under a suitable in-process dressing condition, is widely studied and applied to produce cutting tools made of difficult-to-machine materials (from tungsten carbide to PCD). One of the main objectives in the production of these tools is to generate high precision cutting edges with good quality of surface and sub-surface layers.

From the many properties to describe surface layer (such as surface roughness,

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micro structural hardness variation, metallurgical transformation and residual stresses, etc.), residual stresses may be regarded as the most representative one. On the one hand, they give a good estimate of the phenomena involved in the creation of surface integrity [1] and they affect the functional properties of the component very significantly [2, 3]. As far as cutting tools are concerned, user is interested mainly in the tool life and reliability of the tool, expressed by fatigue limit, which is mainly related to the residual field developed [4, 5]. In addition, residual stresses can have detrimental effects on the cutting edge geometry and result in edges that do not meet specified tolerances. That all makes residual stresses one of the most important parameter of surface layer properties. Hence, it is no wonder that they have been the object of extensive research and a lot of information can be found in literature spread over many different publications and reports. There is, however, lack of commonly accepted data which can allow predicting tool life and reliability of the tool.

One of the primary reasons for this is that a number of issues central to complete understanding of the residual stresses still remain. First, as is generally accepted that the residual stress induced by grinding results from a combination of thermal tensile component and the mechanical compressive component. From these, the thermal component which is believed to be tensile in nature, has extensively been investigated, while only a few studies are reported on the mechanical compressive component [6, 7, 8] These studies do provide some physical basis, however, it is still challenging to provide a quantitative insight on the mechanical compressive component [9] and thus it is difficult to assess the influence of the sum of residual stresses present on the functional behavior of ground parts. Although, simple statements such as “compressive residual stresses increase fatigue life of the tool” are often encountered, it is very important to realize that tool life will largely depend on the interactions among the residual stresses generated during tool grinding and in a subsequent machining operation performed by the tool. In addition, tool life is also affected by the variables like: thermo-mechanical load, type of cutting (e.g., rough cutting ,finish cutting), tool type ,tool geometry , mechanical properties of work& tool material ,cutting conditions, condition of the boundary surfaces between the chip and the rake face of the tool , cutting fluid and many other factors , which are poorly understood at present. Furthermore, residual stresses are difficult to measure accurately using the current experimental techniques due to the small scale nature of the phenomena. The other extreme is the measurement of stress at singular points which hinders the reconstruction of the overall stress state.

In addition to the above it should also be noted that residual stresses in grinding depend strongly on the process parameters. It was reported that by using gentle grinding conditions the surface residual stresses can be reduced and can even become compressive which are beneficial since they increase the fatigue life of ground components (such as shafts and ball bearings) [10, 11]. On the other hand, if the grinding conditions are changed from gentle to abusive, benefit of the compressive residual stress will be outweighed by the induction of cracks which will lower the strength [11]. Thus, one has to identify an optimum grinding condition. However, it is difficult to design optimum grinding conditions based on residual stress criteria since the relationships between the grinding conditions and residual stresses are generally unknown and seem to be sensitive to the microstructure of the workpiece.

Summarizing, we may say that the generation of residual stresses is an extremely complex phenomenon, and all the more so there are a large number of factors influencing the tool life. Consequently, a reliable and consistent prediction of the functional properties of a ground tool seems to be impossible. This is evident from the contradictory results frequently reported in literature about the influence of residual stresses on the wear resistance of ground components or tools [12, 13, 14, 15, 16, 17, and 18]. In practice, when grinding hard metal tools by diamond wheels, parameters like grinding ratio and grinding cost are evaluated for the optimum process conditions. A high grinding ratio generally has a favorable effect above all on the material removal rate (MRR) and as a result grinding cost is reduced. However, this does not mean that a high grinding ratio must always be optimum for obtaining improved tool quality. Attempting to obtain a high grinding ratio in practice is not always desirable because high ratios may indicate grain dulling [19]. As a result, grinding force, temperature and temperature gradient are increased and likelihood or severity of surface damage is increased as well, thereby significantly reducing the functional properties of ground tools.

Based on the above discussions, it can be concluded that based on the available research data about residual stresses and grinding process optimizing parameters like grinding ratio and grinding cost as well as due to non-availability of reliable data on tool life, it is not possible to predict tool life and reliability of the tool.

However, customer today is far more particular than he has been in the past, demanding products of high quality for the lowest possible cost. In his perception, a high quality product is one which performs its functions reliably and at the same time it is economically viable. As stated, a quality characteristic refers to a performance characteristic that affects the final product quality and it is very important to customer [20]. In other words we can say that in the present global scenario there is a new definition of quality, i.e. quality is the stated and implied needs of a customer. In a broader sense, the word ‘Quality’ encompasses a number of significant aspects characterizing the acceptability of a product. Detailed analysis of these aspects can be found in [21, 22, 23, 24, and 25]. If we conclude we can easily say that delivering reliable, high quality products at low cost have become the key to survival in today’s global competition and a consumer driven market. This reflects the realization that like other industries, cutting tool industry should also establish such quality standards which can be economically attained and maintained and yet they provide the desired satisfaction to the customer. This cannot be achieved economically through inspection which involves actual checking of material and components already produced, i.e., the emphasis is on the quality of products already produced. Designing in quality is cheaper than trying to inspect and re-engineer it in after a product hits the production floor or worse, after it gets to the customer [26]. Thus, philosophy of quality engineering must be employed to design high quality products at low cost.

Quality Engineering is defined as “the branch of engineering which deals with the principles and practice of product and service quality assurance and quality control” [27]. Certain experts in quality control have put into larger perspective many of the quality control concepts and methods. Notable among these experts (quality Gurus) are Deming, Juran, and Taguchi, whose philosophies of quality engineering had a major impact on modern manufacturing.

From these, Taguchi’s quality engineering methods have been proved successful for many manufacturing circumstances [28, 29, 30, 31, and 32].These methods are also referred to as robust design [33, 34]. Robust design (RD) is an engineering method of quality improvement that seeks to obtain a lowest cost solution to the product design specification based on the requirements of the customer. Although, Taguchi’s robust design principle has been widely accepted, the methods Taguchi offers for robust design have received much criticism, in particular the two part orthogonal array for experimental design and the “signal-to-noise” ratio(S/N ratio) used as the robust criterion [35, 36]. Furthermore, most previous applications of Taguchi’s RD method only emphasize single response problems, while the multi-response problems have received relatively little attention. However, several correlated quality characteristics of a product are usually considered for product quality by a consumer. Though, there have been many attempts to integrate Taguchi’s robust design principles with established statistical techniques, there is ample scope for applying quality by design concepts, especially when dealing with multi-response variables.

The aim of this paper is to emphasize on the importance of the concept of Taguchi’s quality engineering concepts in order to see the level of importance of grinding parameters on such quality characteristic which is usually considered for tool quality by a customer. This characteristic considers tool life and, consequently, evaluates the total technological cost which includes specific tool grinding cost as well as the cost of subsequent machining operation perform by that tool. In machining operation, the effect of cutting parameters on the tool life is of course very well known. We did not intend to apply Taguchi’s quality engineering methods in optimization of diamond grinding process. We tried to emphasize the importance of Taguchi’s signal-to-nose ratio (S/N ratio) and his quality philosophy in determining the optimum diamond grinding conditions for the above mentioned quality characteristic using a well established statistical technique, known as response surface methodology (RSM).RSM is a methodology that combines experimental designs and statistical techniques, for empirical model building and optimization. By conducting experiments and applying regression analysis, RSM seeks to relate a response to some input variables. A comprehensive review of RSM is presented in [37]. To the best knowledge of the authors, there is no published optimization wok including both tool life and technological cost together on diamond grinding operation applied for producing hard metal cutting tools. An approach considering importance of Taguchi’s S/N ratio and quality philosophy and utilizing the RSM methodology for the optimization of such quality characteristic which is usually considered for tool quality by a customer is an important contribution to the field. This quality characteristic was proposed by the authors. Experimental results are provided in the two response surface plots. In this study, tool insert made of hard metal tool material / STIM-3B (Russian made) was ground under different conditions of grinding speed and cross feed.

2. CONCEPT OF TAGUCHI'S SIGNAL-TO-NOISE RATIO IN GRINDING

During the grinding process, input factors (such as wheel speed, cross feed, abrasive size, etc.) may cause varied relationships of functional factors /process parameters (such as tangential force, normal/tangential force relationship also known as K-value, and grinding temperature), which in turn, will result in the deviation of optimizing parameters from their target values. Even it may happen that under the varied relationships of functional factors, the optimizing parameter can reach their target values. However, the question still remains to be answered on how those different levels of functional factors would influence the tool life and reliability of the tool. According to Taguchi, there are two types of factors that affect a product's functional characteristic: control factors and noise factors. Control factors are those which can easily be controlled (such as wheel speed, cross feed, and diamond grain size in diamond grinding process) .noise factors are factors that are difficult or impossible or too expensive to control. For example , in the same diamond grinding process such factors could be : strength and size variations of individual diamond grains and phases on a single wheel surface alone and in a hard metal workpiece respectively , the state of sharpness of wheel topography , etc. these noise factors are primarily responsible for causing a products performance to deviate from its target value. Hence, Taguchi's parameter design seeks to identify setting of the control factors which make the product least sensitive to variations in the noise factors, i.e., make the product more robust, without actually eliminating the cause of variation. The aim is fulfilled by considering the "signal-to-noise" ratio (S/N ratio) as the measure of performance. A number of S/N ratios are available in Taguchi methods, e.g. smaller the better, larger the better, and nominal the best. The standard S/N ratios can be customized to fit specific applications and new S/N ratios can be developed for particular applications. For example, in our case smaller the better and larger the better are suitable for the technological cost and for the tool life/reliability of the tool respectively.

3. TAGUCHI'S QUALITY PHILOSOPHY

Taguchi's greatest contribution to the area of quality engineering was his quality philosophy. He suggests a different method of measuring quality. **Loss function** measures quality. The loss function establishes a financial measure of the user dissatisfaction with a product's performance as it deviates from a target value. This is a more realistic and useful measure of quality than merely meeting engineering specifications, which may inhibit working toward continuous process improvement.

4. THE PROPOSED QUALITY CHARACTERISTIC

Based on the above concept of quality, authors propose a new quality characteristic for a cutting tool termed as “integral quality characteristic” for a hard metal cutting tool produced by diamond grinding method. This characteristic takes in to account the tool life specified by the length of work cut to failure in meters (L, m) and , consequently, evaluates the technological cost in grivnya (Ct, Grv) which includes : specific tool grinding cost as well as the cost of subsequent machining operation performed by the tool . Hence, in fact reliability of the tool is evaluated in terms of cost as it is well known that cutting tool reliability decreases monotonically with cutting time, therefore, there exists one-to-one correspondence between reliability R (t) and cutting time, t.

Now, let us analyze and compare the proposed characteristic with Taguchi’s Quality Loss Function curve. The Taguchi’s loss function is graphed in figure 1. Without going into detail about the curve, let us focus on some aspects from comparison points of view. In traditional systems, the product is accepted if a product measurement falls within the specification limit; otherwise, the product is rejected. The quality losses occur only when the product deviates beyond the quality specification limit, thereby becoming unacceptable. These costs tend to be constant and relate to the costs of bringing the product back into the specification range. Taguchi suggests a more narrow view of characteristic acceptability by indicating that any deviation from product functional characteristic’s (in our case that is integral quality characteristic of the tool) target value (m) results in a loss see Figure 1. In the same Figure, it may be seen that if the measurement of that characteristic is the same as the target value, the loss is zero. Otherwise the loss can be measured by using quadratic function, after which actions are taken to reduce systematically the variation from the target value.

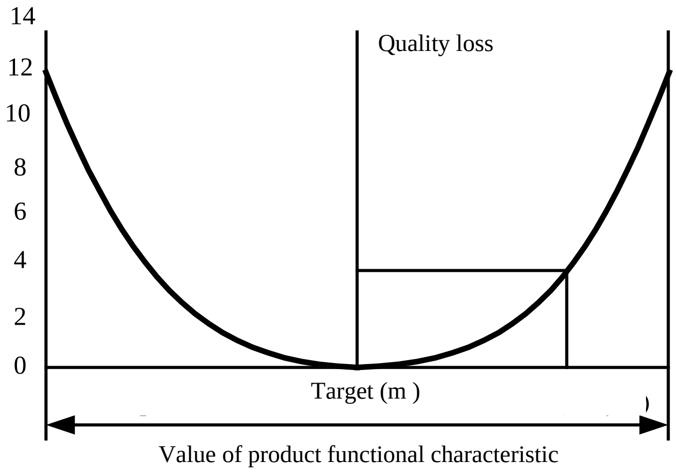
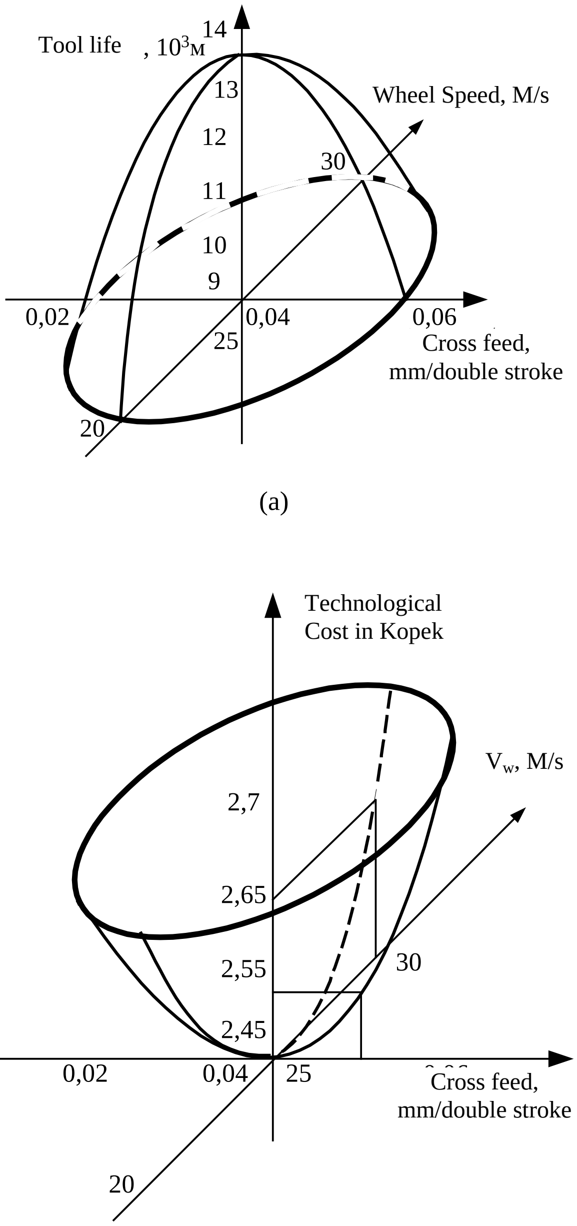


Fig. 1. Quality loss function in terms of the value of product functional characteristic – quality loss increases with deviation from the target value, m.



(a)

(b)

Fig. 2. The response surface plot of:
(a). Tool life as a function of cross feed and grinding speed;
(b). Technological cost as a function of cross feed and grinding speed.

5. ANALYSIS AND DISCUSSION OF THE EXPERIMENTAL RESULTS

In this study, the response surface methodology was used in determining the optimum diamond grinding conditions for hard metal tool using the two most influential grinding process input parameters: grinding speed and cross feed. Experimental results are shown in Fig.2 (a) and (b). The length of work cut to failure of the cutting tool, L, and the technological cost, Ct, in relation to the input parameters are shown in Fig 2 (a) and (b) respectively. Length of work cut by the ground tool (tool life) is an index which determines the technological cost. Accordingly, its minimum value would correspond to the prolonged tool life. In the Fig. 2 (b), it may be seen that with the decrease in the values of process input parameters, technological cost decreases which means that the tool ground under the gentle grinding conditions has a prolonged life. The obtained results give a kind of evidence that additional cost in tool grinding is due to the low values of process inputs parameters and, therefore, there is an increase in the specific grinding cost which is recovered by the reduced total technological cost (decrease in quality loss). As a result, there is an enhancement of cutting tool quality (wear resistance).

More narrow the ranges of grinding speed and feed, lesser is technological cost which can be considered analogous to quality loss function, and hence it can be said that the integral grinding quality characteristic proposed by us is the financial measure of the user dissatisfaction with the cutting tool's performance as it deviates from a target value. Also, it may be seen in the Fig. 2 (b) that as we move away from the optimum values of process input parameters, customer dissatisfaction increases. So, the part of the response surface nearing the optimum grinding conditions may be considered as similar to the Taguchi's loss function as graphed in Figure 1.

6. CONCLUSIONS

Due to very complex nature of residual stresses and insufficient research data on them as well as due to non-availability of reliable data on tool life and grinding process optimizing parameters like grinding ratio and grinding cost, it is not possible to predict tool life and reliability of the tool. However, production of reliable and high quality products at a relatively low cost has become key to survival in today's global competition and a consumer driven market. Designing in quality using Taguchi's quality engineering concepts is considered to be an effective approach to improve product quality at lowest cost. However, these approaches are subjective in nature and always brings an element of uncertainty to the decision making process. Therefore, an alternative approach using response surface methodology at the same time keeping in sight Taguchi's quality engineering concepts, has been used in this study. Based on the experimental results, conclusions are drawn as follows:

1. If to consider manufacturing tolerances or quality characteristic's deviation range as one of the factors influencing the overall cost of the product, then

it may be concluded that the concept of quality engineering is closely related to the experimental design procedures, particularly when the quality characteristics are considered for product quality by a consumer;

2. The application of the quality engineering concept in optimization of grinding process is directed towards satisfying cross-functional goals as quality, cost, manpower development, quality of work life, etc. These activities ultimately lead to an increased customer and Employee satisfaction.

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