Archives of Current Research International
3(4): 1-6, 2016, Article no.ACRI.24800
ISSN: 2454-7077

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New Insight into the Machined Surface Micro-roughness and the Tool Feed Relation

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Authors' contributions

This work was carried out in collaboration between all authors. Author KV formulated research issues and hypothesis of presented problem and designed the research. Author ZM methodically managed experiments and evaluated results. Author JN, a PhD student, conducted experiments directly on machine tools. All authors read and approved the final manuscript.

Article Information

DOI:10.9734/ACRI/2016/24800
Editor(s):
(1) R. M. Chandima Ratnayake, Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Norway.
Reviewers:
(1) Kais Raad Abdul Majeed, ISF Medical Centre, Doha, Qatar.
(2) Siva Prasad Kondapalli, Anil Neerukonda Institute of Technology and Sciences, India.
Complete Peer review History: http://sciencedomain.org/review-history/14150

Short Research Article

Received 1st February 2016
Accepted 25th March 2016
Published 14th April 2016

ABSTRACT

The paper presents research results of analyzing the relation between the machined surface micro-roughness and tool feed *f* and thus introduces new insight into a problem comparing the experimental and theoretical results. During evaluation of profile records and theoretically defined rounded tool tip, the considerable disproportions can be found. In practice, this fact leads to incorrectly determination of tool feed for required value of *Rz* and selection of tool tip radius r_ε. The aim of the paper is to identify the reasons of such disproportions and suggest a method of their elimination by finding the more precise relation *Rz*-*f* as the standard well-known relation is. The many experiments were performed testing the low carbon steel machined by coated sintered carbide and ceramic tools.

Keywords: Tool geometry; feed; machined surface; tool tip radius.

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1. INTRODUCTION

The method of determination of tool feed *f* regarding the surface roughness parameter value *Rz* and tool tip radius r_ε is based on presumption of precise copying of tool tip along machined surface. However, the machining of whole range of mechanical engineering materials has shown the large differences in obtaining the highest or medium arithmetic roughness height. It is caused by plastic deformation of machined material in contact with rounded tool cutting edge. Therefore it is necessary to modify the well-known theoretical relation (3). This paper is an attempt to make objectification of this relation.

The factors affecting the surface roughness and major investigators are introduced in [1]. In [2] is summarized the parameters that affect surface roughness. The initial surface roughness models considered variables of cutting speed and feed rate. The next developed models have involved workpiece hardness, tool tip radius, depth of cut, effect of cutting fluid, built up edge etc. Some authors focus on surface roughness in milling [3-5] and in turning [6]. The modern trends are based on prediction using Artificial Neural Networks, Fuzzy Logic and Genetic Algorithms. [5] Thus, the models for prediction the surface roughness can be classified as the experimental, analytical and Artificial Intelligence models.

The tool tip is rounded with $r_\varepsilon \leq f$. Surface profile is created only by rounded tool tip. This case represents surface finishing. Fig. 1 shows two tool positions offset by feed.

In case that the tool is of the tool tip radius r_ε, the theoretical value *Rz* is determined by following way regarding Fig. 1:

$$Rz = \mathrm{ED} - \mathrm{EC} = \mathrm{ED} - \sqrt{\mathrm{CO}_1^2 - \mathrm{EO}_1^2} \qquad (1)$$

Using substitution $\mathrm{ED} = AO_1 = r_\varepsilon$, we obtain:

$$Rz = r_\varepsilon - \sqrt{r_\varepsilon^2 - \frac{f}{2}} \qquad (2)$$

Because value Rz^2 is very small in comparison with $2\,Rz\,r_\varepsilon$, it can be neglected and the well-known relation ([7-11]) follows:

$$Rz = \frac{f^2}{8\ r_\varepsilon} = 0.125\,\frac{f^2}{r_\varepsilon} \qquad (3)$$

The frequently used relation (3) introduces the dependence between theoretical surface roughness, feed and tool tip radius. Therefore *Rz* raises quadratic with the growth of feed *f*. However, according to the law of hyperbola, *Rz* decreases with the increase of tool tip radius r_ε. The relation (3) is commonly used for the determination of feed for pre-required value *Rz* of machined surface.

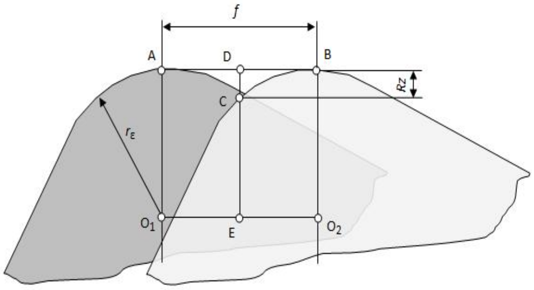

Fig. 1. Scheme of micro-roughness during surface finishing

For instance, if a pre-required value *Rz* is 10 µm and cutting insert is of tip radius r_ε = 1 mm, then the feed *f* according to (3) is:

$$f = \sqrt{Rz\,8\,r_\varepsilon} = \sqrt{0.01\mathrm{mm}\ \mathrm{x}8\ \mathrm{x}1\mathrm{mm}} = 0.283\,\mathrm{mm} \quad (4)$$

If this feed cannot be set on the lathe, the nearest lower one is selected. In this case it is 0.27 mm.

Fig. 2 presents a complete graph of relationship *Rz*=f(*f*, r_ε) calculated according to the theoretical relation (3). The typical parabolic dependence between *Rz* and *f* results from graph. The curves start at zero and sharply rise with small tip radii. The increase of cutting edge radius r_ε leads to the decrease of *Rz* in whole range of feed rates.

2. MATERIALS AND METHODS

The experiments were performed by turning the steel C45 by tools of cemented carbide P20 involving TiN coating and Al_2O_3. The constant cutting speed was complied in experiments. All experimental curves were compared with the theoretical curve determined by calculation of the equation (3). The feed rates were set in range from the minimum adjustable on the lathe up to 1 mm. The surface roughness was measured by profilometer Mitutoyo 301.

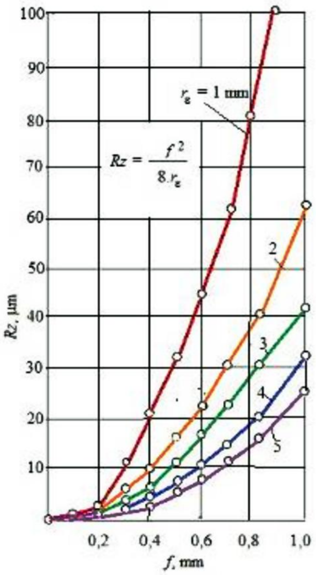

Fig. 2. Graphs of theoretical function *Rz*=f(*f, r_ε*) for machining by a rounded tool tip cutting tool of radii 1-5 mm

3. RESULTS AND DISCUSSION

We have verified the theoretical dependences in real machining. Fig. 3 provides a graph of experimental dependence of *Rz* on r_ε and *f* for r_ε =1 mm.

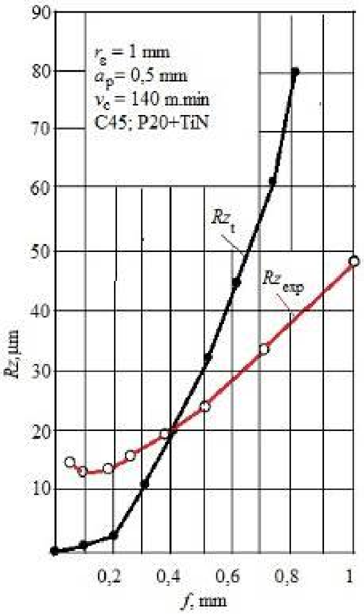

Fig. 3. Experimental dependence between Rz, feed and tool tip radius, workpiece: C45, tool: P20+TiN, v_c= 100 m.min^{-1}

If the Rz_{exp} graph curve is compared with the theoretical Rz_t (lower index t means theoretical *Rz* value) graph curve, the considerable differences can be seen. In comparison with previous calculation, while the set feed value according to (3) is *f*=0.27 mm, the reached value is *Rz* ≈ 17 µm, which is a much higher as theoretical Rz_t value. The experimental graphs do not start at zero. On the other side, if feed is lower than 0.1 mm, *Rz* values increase. This is the reason why it is practically not possible to obtain the better quality of machined surface by decreasing the feed less than 0.1 mm. The reason is obvious in Fig. 4. In case of minimal thicknesses of cut depth, the cut material is being pushed under the cutting wedge. Both curves intersect only in the feed rate value 0.4 mm. The significant plastic deformation appears and the deformed material relaxes after passing the cutting wedge and creates roughness of machined surface. It is necessary to note that the cutting edge radii of tools made of sintered carbide are in hundredth of millimetre.

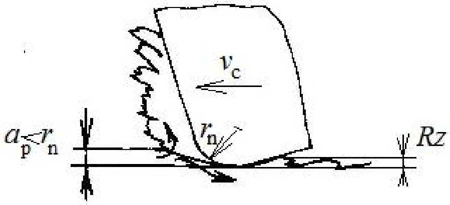

Fig. 4. Mechanism of material deformation before the cutting wedge in case of minimal cut depth a_p

The result of the mechanism of pushing out the material from under the rounded cutting tool edge can be seen in Fig. 5.

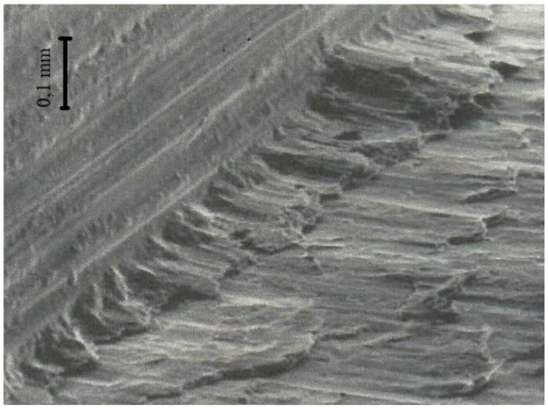

Fig. 5. Chip formation and machined surface at small cut depth

The extra negative case is when a built-up edge on tool cutting wedge appears. Fig. 6 shows the metallographic micro-section of the chip formation zone of minimal cut depth and the presence of the built-up edge. The different friction conditions occur between cut material and built-up edge material. The “plastic cutting edge” radius, i.e. the built-up edge, is much larger than that of the tool.

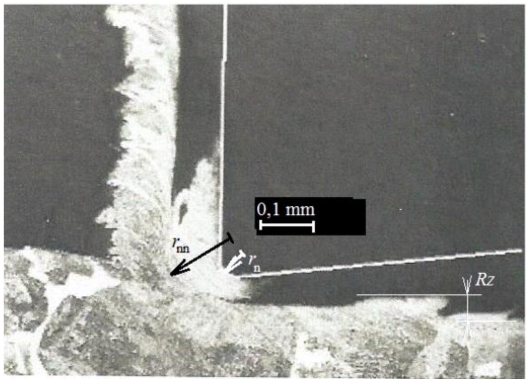

Fig. 6. Metallographic micro-section of the chip formation zone with the built-up edge on the cutting wedge, cut material: C45, v_c = 40 m.min^{-1}, f = 0.075 mm; r_n – radius of cutting edge, r_{nn} – radius of built up “cutting” edge, *Rz* – mean roughness depth

Fig. 7 shows that the plastic compressing of material under cutting tool wedge is followed by its relaxation. The numerous small "chips" are on the machined surfaces accompanied cracks that are extended below the machined surface. Machined surface is rough. The surface roughness profile is shown in Fig. 8 obtained by profilometer. In experiment the various radii of curvature of the cutting edge were used. The size of the feed cannot be identified from the record in Fig. 8.

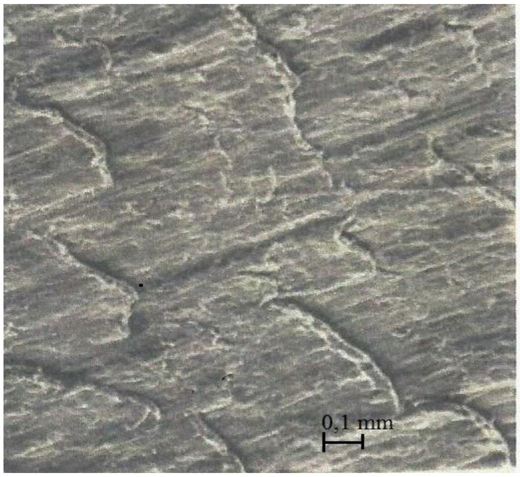

Fig. 7. Surface with plastic deformation signs machined by rounded cutting edge tool [5]

According to watched aspect – *Rz* value, mainly left parts of graphs are important, as *Rz* is essential for finishing, i.e. for low feed rates. Fig. 9 presents theoretical and experimental curves for tool tip radius 3 mm. In comparison with Fig. 3, the intersection point of both curves is moved higher, towards the feed of 0.7 mm. Even larger difference between theory and experiment is for machining by a ceramic cutting tool inserts (Fig. 10). The cutting edge radius of ceramic cutting tool insert is considerably larger than that of sintered carbide tool. In that case it is 0.8 mm (Fig. 10).

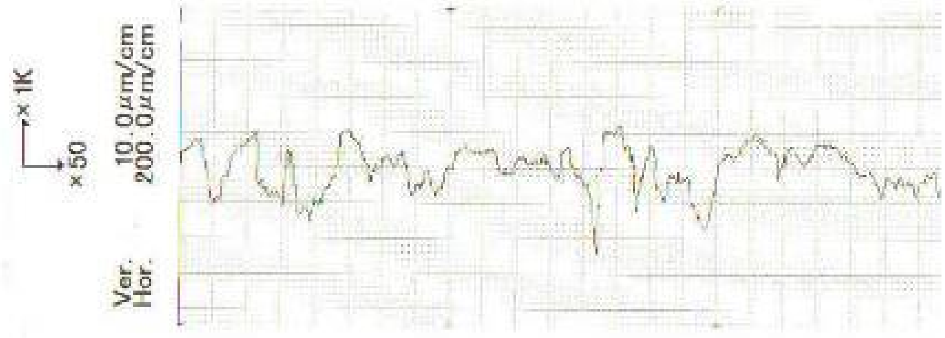

Fig. 8. Record of machined surface micro-geometry in Fig. 7

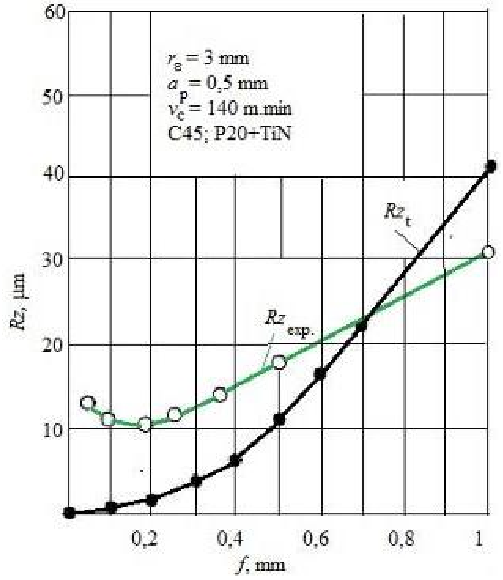

Fig. 9. Experimental and theoretical graph curves of dependence *Rz – f* for tool tip radius $r_ε$ = 3 mm

Theoretical Rz_t values increase rapidly for feeds smaller than 0.1 mm, but experimental values Rz_{exp} decrease rapidly while Rz_{exp} is larger than Rz_t. Thereafter, exceeding the feed value 0.15 mm, all experimental values Rz_{exp} are lower than theoretical Rz_t . Therefore it is possible to use the much larger feed to obtain required value *Rz* what means the reducing of machining time. In this case the equation (3) cannot be used at all.

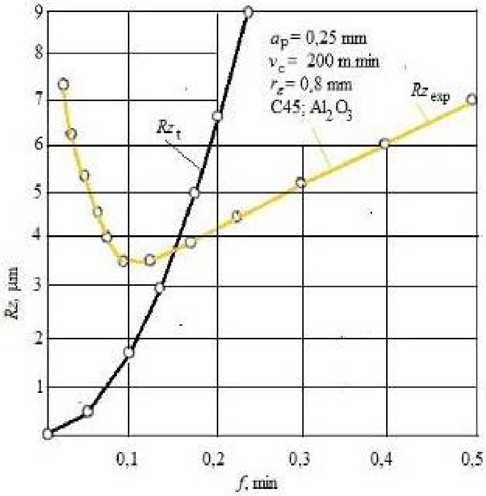

Fig. 10. Theoretical and experimental dependence *Rz - f* for machining with a ceramic tool

The generalization of experimental dependence *Rz-f* is presented in following part.

3.1 Analytical Determination of Relation

The realized experiments pointed out the need of equation (3) modification. From the experiment data set, a characteristic dependence curve *Rz-f* has been made (Fig. 11). In this case the graph curve is for the tool tip radius $r_ε$ = 0.8 mm.

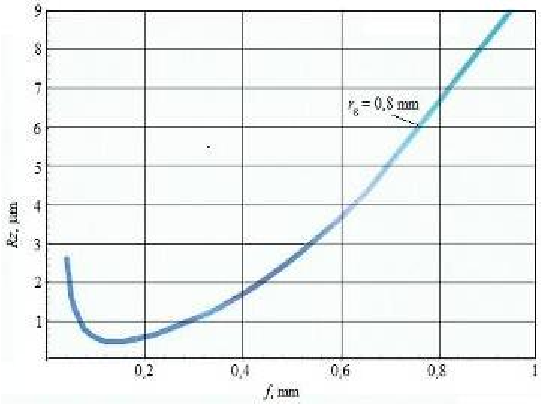

Fig. 11. Characteristic dependence curve Rz_{exp} - *f*, tool tip radius: $r_ε$ = 0.8 mm

The goal is to replace the original theoretical formula (3) for feed calculation by a "practical" one. As there is already an equation, it is possible to express the feed *f,* which is necessary for further process of solution. Brammertz [12] in 1961 defined the following formula:

$$Rz = \frac{f^2}{8 r_\varepsilon} + \left(1 + \frac{r_\varepsilon}{f^2}\right) \qquad (5)$$

After determination of variable *f*, there is an assumption of more correct prediction in real conditions. The corresponding relation is following:

$$f = \sqrt{8\,Rz\;r_\varepsilon - 2\;r_\varepsilon + 4\;r_\varepsilon \sqrt{Rz^2 - Rz}} \qquad (6)$$

The formula (6) for the calculation of the feed corresponds with practical conditions of machining. As an aid for the technologist, a simple calculation programme can be made.

4. CONCLUSION

The paper analyses recent approach of determination of the feed for required values of Rz and r_ε. Moreover, the paper identifies inaccuracies disproportions created using theoretical relation $Rz=f(f, r_\varepsilon)$. The result is a suggestion of a new equation of surface roughness with more precise determination of the feed. It can be supposed that this is the way towards the objectification of technology stage of production preparation. There is a limit feed value (about 0.1 mm) below which the profile mean roughness depth Rz rising. This is due to the size of the radius of the rounded cutting edge r_n. As shown, the most significant disproportion between theoretical and practical curves Rz-f is for machining by the ceramic tool. It is known that the radii of curvature of the cutting edge of ceramic tools are of the order of tenths of mm. Therefore Rz under feed 0.1 mm significantly increased. The analyzed and presented facts must be considered by the technologist when selecting cutting conditions, mainly feed.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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