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A. Orgiyan, DSc., Prof.,
G. Oborskyi, DSc., Prof.,
A. Balaniuk, PhD, Assoc. Prof.,
V. Kolesnik, PhD, Assoc. Prof.
V. Dotsenko, PhD, Assoc. Prof.
Odesa Polytechnic State University, 1 Shevchenko Ave., Odesa, Ukraine, 65044; e-mail: annabalanyuk24@gmail.com

INFLUENCE OF CUTTING MODES ON WEAR RESISTANCE OF CUTTERS AND ACCURACY OF FINE BORING OF STEELS

О.А. Оргіян, Г.О. Оборський, Г.В. Баланюк, В.М. Колеснік, В.П. Доценко. **Вплив режимів різання на зносостійкість різців та точність тонкого розточування сталей.** У роботі експериментально досліджено процеси тонкого розточування сталей, що забезпечують підвищення продуктивності та параметрів точності обробки. Шляхом варіювання режимів різання та спеціальної геометрії твердосплавних різців зі стружкозавиваючими фасками визначено умови, що забезпечують високу зносостійкість різальних лез, підвищення параметрів точності та якості обробки. В експериментах використовувалися однорізцеве розточування, а також дворізцеве оброблення методом розподілу подачі. На основі методу планування експерименту за наявності великої кількості вхідних параметрів, що варіюються, встановлені раціональні величини швидкості, подачі, глибини різання, а також параметри шорсткості, конусності і відхилень від круглості оброблених отворів. Уточнено вплив режимів тонкого розточування на зношування та стійкість ріжучих кромок. Вивчався також вплив податливості консольних борштанг на рівень коливань різця. Встановлено, що для борштангу малого діаметра <10 мм при глибині різання >0,1 мм виникають інтенсивні вібрації, що призводять до інтенсивного зносу різців. У попередніх експериментах встановлено, що розточування м'яких сталей (типу 20Х і сталі 30) значною мірою відрізняється від обробки твердіших сталей і вимагає застосування інших режимів різання. Хоча групи конструкційних вуглецевих, якісних і легованих сталей за умовами обробки та досягнутими в процесі тонкого розточування результати можуть відрізнятися незначно, проте при обробці сталей зі спеціальними властивостями виникає відмінна особливість – зростання рівня коливань зі збільшенням швидкості різання в інтервалі застосовуваних для інших сталей швидкостей. В роботі отримані результати експериментального дослідження процесу тонкого розточування сталі 35Л різцями з твердого сплаву Т30К4 і стружкозавиваючими фасками вздовж різальних лез.

Ключові слова: зносостійкість, точність, геометрія різців, одно- та дворізцеве розточування, режими різання

A. Orgiyan, G. Oborskyi, A. Balaniuk, V. Kolesnik, V. Dotsenko **The influence of cutting modes on wear resistance of cutters and accuracy of fine boring of steels.** This paper is devoted to experimental study of fine boring of steels, which improves performance and parameters of processing accuracy. The conditions that ensure high wear resistance of cutting blades and improvement of accuracy parameters and processing quality were determined by changing cutting conditions and special geometry of carbide cutters with chip-curving chamfers. In the experiments, single-cutter boring was used, as well as double-cutter according to the feed division method. On the basis of the method of planning an experiment in the presence of a large number of variable input parameters, rational values of speed, feed, depth of cut, as well as parameters of roughness, taper and deviations from the roundness of the machined holes are established. The effect of fine boring modes on wear and tool life of cutting edges has been clarified. The influence of the compliance of cantilever boring bars on the level of oscillation of the cutter was also studied. It was found that intense vibrations occur for boring bars of small diameter <10 mm at a depth of cut >0.1 mm, resulting in intensive wear of the cutters. In preliminary experiments, it was found that boring of soft parts (type 20X and steel 30) is significantly different from machining harder steels and requires the use of other cutting conditions. Although the groups of structural carbon, high-quality and alloy steels may differ insignificantly in terms of processing conditions and the results achieved in the process of fine boring, however, for processing steels with special properties, a distinctive feature arises, namely increase in the level of vibrations with increasing cutting speed within the range usually used for other steels. This paper shows results of an experimental study of the process of thin boring of 35L steel with cutters made of T30K4 hard alloy and chip-curving chamfers along the cutting blades.

Keywords: wear resistance, accuracy, cutter geometry, single- and double-cutter boring, cutting modes

Introduction

Fine boring of steels results in flow chips, wear along both the front, and rear surfaces of the tool. Under such conditions of wear, the hard alloy 130K4 shows good performance, which is distinguished by the highest wear resistance [1] in comparison with other hard alloys.

The groups of structural carbon, high-quality and alloy steels differ insignificantly in terms of processing conditions and results achieved in the process of fine boring. Steel 40X is peculiar for these

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groups and the most widely used in production. The best conditions for fine boring of 40X steel are obtained when operating at cutting speeds of approximately 140 m/min. The bore diameter has a significant effect on the tool life. The roughness of the surface with the correct assignment of the geometry of the tool is within the range of $Ra = 0.8...1.6$ µm [2]. The supply of coolant (lubricating and cooling chips) to the cutting zone increases the tool life by 20...25 % and reduces roughness of the machined surface [3]. It is advisable to apply coolant to the cutting zone under pressure, which also helps to remove chips.

Boring mild steels (type 20X and steel 30) is very different from machining harder steels and requires different cutting conditions. This is conditioned by the fact that boring steel within cutting speed range of 100...120 m/min results in formation of build-up, which increases the surface roughness. Only an increase in cutting speeds up to 200...300 m/min makes it possible to obtain holes with a roughness $Ra = 0.8...1.6$ microns. Particular difficulties arise during fine boring of various steels with special physical and chemical properties (stainless steels, heat-resistant, heat-resistant, etc.). The influence of dynamic interactions in fine finishing boring is one of the main factors that determine the wear resistance of the cutters and the accuracy of the machined surface [4, 5].

Analysis of last publications and problem statement

Analysis of literature sources allows you to determine the features of steel boring.

Feed affects tool life in the same way as when boring cast iron. In this case, the results are also obtained at feed speed f 0.04...0.05 mm/rev [6]. The effect of the depth of cut during thin boring of 40X steels is greater than when machining cast iron, which is due to a change in the nature of chip formation in the process of cutting plastic material. The effect of a change in cut depth on the tool life is especially significant at low rigidity of the elastic system of the machine in conditions of machining holes of small diameters. In this case, an increase in the depth of cut over 0.1 mm can lead to vibrations and intense tool wear. In case of excessive decrease in the depth of cut, the tool is elastically deformed and does not completely cut thin layers of metal, quickly losing its durability [7].

Tool wear and tool life when boring steel 40X is significantly influenced by the geometry of the cutting part of the tool. The most rational values of the rake angle when machining steel are within the range $\gamma = -5...10°$. The value of the main clearance angle is usually selected within the range of 6...12°, depending on the diameter of the bore. Large boring diameters allow the use of a rigid tool and then the clearance angle can be 6...8°. Small values of the clearance angle ensure greater dimensional tool life and, accordingly, a higher machining accuracy [8]. The highest tool life is achieved with fine boring of steel with cutters at entering angle $\varphi = 45...60°$ and side cut angles $\varphi_1 = 10...20°$.

Corner radius is usually within the range of 0.1...0.3 mm. The use of a wiper blade instead of a radius of curvature reduces the surface roughness and the amount of relative wear. It also allows increasing feed speed [9].

Particular difficulties arise in fine boring of various steels with special physical and chemical properties (stainless steels, heat-resistant, heat-resistant, etc.) The processing volume of such steels is growing due to their wider use in the industry. The specificity of the properties of these steels (low thermal conductivity, the presence of carbide inclusions) leads to the fact that when machining at cutting speeds usually used for fine boring of structural steels, cutting tools wear out quickly. In this regard, the cutting speeds have to be adjusted in comparison with the recommended values.

The specific feature of the processing of steels with special properties is an increase in vibration level and cutting speed in the range that is common for other steels. Change in vibration with increase of cutting speed results in corresponding fluctuations in relative wear. Similarly, to the change in the vibration level of the tool, the roughness of the machined surface [10, 11] also changes.

The amount of surface work hardening significantly depends on the rigidity of the elastic system of the machine. The increase in flexibility of spindle block- boring bar, the intensity of vibrations [12] increases. The impact character of the impact of the cutter blade on the surface to be treated increases the work hardening of the metal and increases the microhardness of the processed surface.

The supply of coolant under pressure to the cutting zone has a positive effect on the processing of special steels. In some cases, it is advisable to use lubricants that are applied to the surface of parts before processing. This increases tool life and improves surface quality [13].

Upon dynamic analysis of the spindle-boring bar system and fixture, it is necessary to consider that this process system is limited to cutting process. When modeling the equations of motion, the main parameters are as follows: the ratio of the natural frequencies of the elastic system and the frequencies of disturbances from external factors, the ratio of the vibration amplitudes in idle and cutting mode, parameters of dynamic stiffness, damping, and vibration resistance parameters [14]. Dynamic vibration dampers [15] are often used to reduce the level of vibrations. The study of interaction of bending and torsional vibrations when machining long holes of small diameter (<12 mm) is the most relevant [16].

The purpose of work

The purpose of this work is to experimentally study the process of thin boring of 35L steel with cutters made of T30K4 hard alloy with chip-curving chamfers along the cutting edges. To achieve the set goal, the following tasks are set in the work:

1) to develop a methodology for conducting an experiment;
2) determine the factors being investigated;
3) determine the variable parameters of cutting conditions;
4) determine the efficiency of the cutting process with single-cutter thin boring and when boring with two oppositely directed cutters by feed division method.

Statement of the main material

35L is commercial quality, linear steel with 0.3 % carbon. Industrial use: rolling mill beds, gear wheels, rods, valves, rollers, rolls, brackets and other parts under the influence of average statistical and dynamic loads. The use of preliminary heat treatment, leading to a refinement of the structure and an increase in its homogeneity, provides optimal properties of cast steel parts for precision engineering and instrument making. The details are characterized by the Brinell hardness value HB = 150...160. Mechanical characteristics, as well as porosity, significantly depend on the heat treatment modes [17].

In the process of research, the technique of active experiment was used with the simultaneous variation of the values of all factors. The experiments were carried out in two stages:

– the first stage is single-cutter thin boring;
– the second stage is boring with two opposite cutters using the feed division method.

Based on production experience and the results of previous research, cutters with chip-curving chamfers along the cutting blades of the following geometry were used (Fig. 1):

1) entering angle $\varphi = 75^\circ$;
2) minor cutting-edge angle $\varphi = 10^\circ$;
3) front rake angle $\gamma = -5^\circ$;
4) inclination angle of main cutting tool $\lambda = 0^\circ$;
5) primary angle $\alpha = -5^\circ$;
6) secondary angle $\alpha_1 = -5^\circ$;
7) chamfers 0.5×15° to the front surface of the cutter.

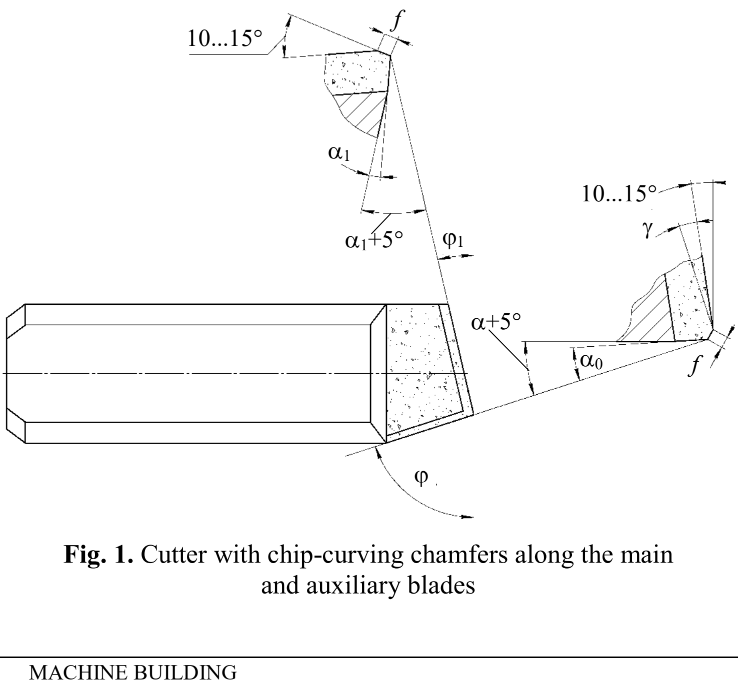

Fig. 1. Cutter with chip-curving chamfers along the main and auxiliary blades

The parameters of the cutter listed above did not change during the research.

The following factors were accepted:

1) cutting speed;

2) feed;
3) cutting depth;
4) cutter corner radius.

During the research, the following parameters were measured:

1) roughness of the treated surface;
2) relative wear of cutters;
3) taper rate of holes;
4) the durability of the cutters.

The influence of the investigated factors on the output parameters of the process was investigated when boring samples made of 35L steel (bore diameter 70 mm, length 60 mm) with a boring bar 100 mm long and 50 mm in diameter. The flexibility of the boring bar in the cutter section is 0.5 μm/kg.

Experiment planning matrix of type 2^{4-1} was adopted based on number of studied factors (Table 1).

Table 1

Experiment planning matrix of type 2^{4-1}

Parameters	Factors			
	A, m/min	*B*, mm/rev	*C*, mm	*D*, mm
Main level	150	0.1	0.15	0.3
Variation interval	50	0.06	0.05	0.1
Upper level (+)	200	0.16	0.2	0.4
Lower level (–)	100	0.04	0.1	0.2
Code designation	X_1	X_2	X_3	X_4
Experiment number				
1	–	–	–	–
2	+	+	–	–
3	+	–	+	–
4	+	–	–	+
5	–	+	+	–
6	–	+	–	+
7	–	–	+	+
8	+	+	+	+

The second stage is two-cutter thin boring by feed division Fig. 2.

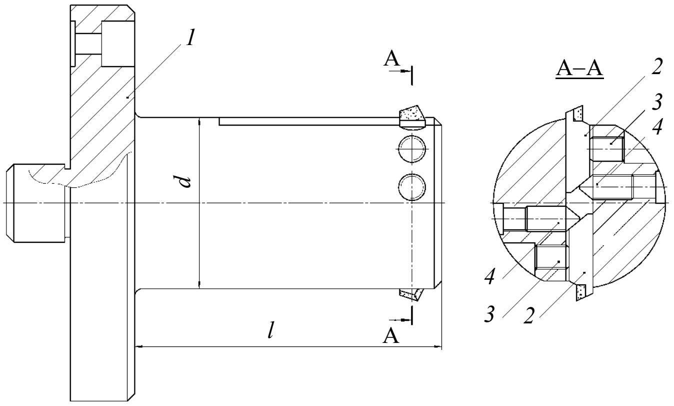

Fig. 2. Boring bar design: *1* – boring bar; *2* – cutters; *3* – clamping screws; *4* – screws for adjusting cutters overhang

Based on the results of the first stage, the optimal cutting conditions were selected, in which the influence of feed on the output parameters of the process was investigated. At the selected feeds, the resistance of the cutters was checked by surface roughness and wear.

The studied factors varied within the following limits:

1) cutting speed: 100...200 m/min;
2) feed: 0.04...0.16 mm/rev;
3) cutting depth: 0.1...0.2 mm;
4) cutter corner radius: 0.2...0.4 mm.

Research results

Based on the adopted planning matrix and the levels set for each factor, an experimental plan was drawn up (Table 2). The results of measuring the surface roughness of the relative wear of the cutters and the taper ratio of the holes in each experiment, performed in strict accordance with the experimental plan, are given in Table 2.

Table 2

Experiment plan for thin boring of 35L steel and obtaining experimental results (cutters made of T130K4 hard alloy: ∅ 12 mm, $\varphi = 75°$, $\varphi_1 = 10°$, $\lambda = 0°$, $\gamma = -5°$, chamfers along the cutting edges 0.5 mm at an angle of 15° to the front surface of the cutter)

Factors	*v*, m/min.	*s*, mm/rev.	*t*, mm	*r*, mm	Output parameters		
					Ra, µm	U_O, µm	*K*, µm
Main level	150	0.1	0.15	0.3			
Variation interval	50	0.06	0.05	0.1			
Upper level (+)	200	0.16	0.2	0.4			
Lower level (–)	100	0.04	0.1	0.2			
Code designation	X_1	X_2	X_3	X_4	Y_1	Y_2	Y_3
Experiment number							
1	100	0.04	0.1	0.2	1.7	12	7.5
2	200	0.16	0.1	0.2	2.6	18	3.0
3	200	0.04	0.2	0.2	1.3	11	7.5
4	200	0.04	0.1	0.4	1.1	8	6.0
5	100	0.16	0.2	0.2	3.2	23	4.0
6	100	0.16	0.1	0.4	2.9	21	3.5
7	100	0.04	0.2	0.4	1.8	12	8.0
8	200	0.16	0.2	0.4	2.4	16	2.5

The coefficients of linear equations for the investigated output parameters of the fine boring process are given in Table 3.

Table 3

Coefficients of linear equations for the investigated output parameters of the fine boring process

Factors		a_0	*v*	*v*	*t*	*r*
Code designation			X_1	X_2	X_3	X_4
Coefficients of linear equations	For Ra	2.125	0.275	+0.65	+0.05	–0.075
	For U_0	15.1	–1.875	+4.375	+0.375	–0.875
	For *K*	5.25	–0.5	–2.0	+0.25	–0.25

By substituting the calculated coefficients with their signs into the equation:

$$Y = a_0 + a_1X_1 + \ldots\ldots + a_nX_n.$$

We obtain:

$$Y_1 = 2.125 - 0.275X_1 + 0.6X_2 + 0.05X_3 - 0.075X_4;$$

$$Y_2 = 15.1 - 1.875X_1 + 4.375X_2 + 0.375X_3 - 0.875X_4;$$

$$Y_3 = 5.25 - 0.5X_1 - 2.0X_2 + 0.25X_3 - 0.25X_4.$$

In these equations, Y_1, Y_2, Y_3 – 5 are coded designations of Ra, U_0 and *K*:

$$X_1 = \frac{v - 150}{50}; \qquad X_2 = \frac{s - 0.1}{0.06};$$

$$X_3 = \frac{t - 0.15}{0.05}; \qquad X_4 = \frac{r - 0.8}{0.1}.$$

The substitution of the coded values of the factors after the transformations into the above equations gives following mathematical models of the process (formulas), which make it possible to calculate the value of the roughness of the machined surface, the relative wear of the cutters and the taper of the bore holes, depending on the adopted values of the factors:

$$\mathrm{Ra} = 1.95 - 0.006v + 10.85s + 1.0t - 0.75r,\ \mu\mathrm{m};$$

$$U_O = 14.9 - 0.04v + 73s + 7.4t - 8.7r,\ \mu\mathrm{m};$$

$$K = 10.1 - 0.01v - 33.4s + 5.0t - 2.5r,\ \mu\mathrm{m}.$$

The analysis of the coefficients of the equations shows that an increase in cutting speed has a positive effect on the output parameters of the fine boring process. However, an increase in the cutting speed above 250 m/min causes tool vibrations and increase of relative wear of the cutter. In this regard, 35L steel processing process shall be carried out at cutting speeds of 200...250 m/min (Fig. 3).

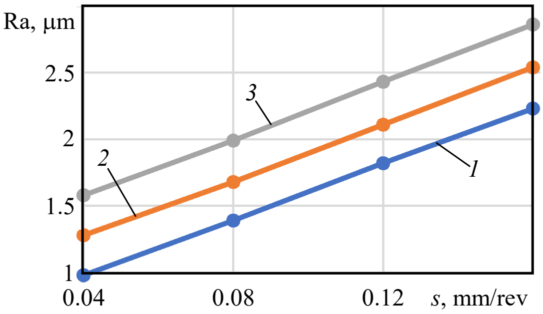

Fig. 3. Influence of feed on surface roughness during boring of 35L steel with cutters with chip-lapping chamfers at different cutting speeds: *1* – *v* = 200 m/min; *2* – *v* = 150 m/min; *3* – *v* = 100 m/min

Roughness of the machined surface, the relative wear of the cutter and the taper of the bore holes are decreased due to increase of cutter corner radius.

However, at the same time, the radial component of the cutting force increases slightly and vibrations of the boring bar occur at radii greater than 0.5 mm. In addition, at large radii of curvature of the tip of the cutter, it is difficult to accurately execute chip-making chamfers on the front surface of the cutter, the line of intersection of which must pass strictly through the tip of the cutter. If this condition is not met, the chip-lapping process is disrupted, which leads to a deterioration in the quality of processing. In this regard, the radius of curvature of the tip of the cutter should not exceed 0.3...0.4 mm.

The depth of cut has a negative effect on all process parameters. The cut depth results in the increase of roughness height on the machined surface, cutters wear rate, and the taper ratio of the hole. From this point of view, it is advisable to use the minimum depth of cut. However, the depth of cut should not be reduced below 0.1 mm, since in this case, the machining results may be affected by the offset of the allowances and unprocessed areas will remain on the surface of the hole.

With an increase in feed, the roughness of the processed surface slightly increases. The feed has the greatest influence on the relative wear of the cutters. An increase in feed causes a sharp increase in the intensity of wear, in connection with which the tool life of the cutters is significantly reduced. Therefore, the machining of 35L steel with carbide cutters at high feed rates turns out to be practically impossible. Since cutting path within the part decreases with increase of feed rate, then, despite the increase in the relative wear of the cutters, the taper of the holes decreases slightly.

The tool life and wear of the cutters were tested at optimal cutting conditions. The relative wear of the cutters was within 8 microns per 1 km of the cutting path, and the taper of the holes was within 5...6 microns.

The technological capabilities of twin-cutter boring by dividing the feed were tested on the optimal cutting conditions and geometric parameters of the cutters selected according to the results of the 1st stage ($v = 200$ m/min; $t = 0.1$ mm; $r = 0.3$ mm). Some comparative experimental results are shown in Figure 4, 5 and 6.

Experiments have shown that when processing by feed division method, the feed value can be increased to 0.06...0.08 mm/rev. If feed rate is 0.06 mm/rev, the tool life is within 4...6 km of the cutting path at Ra = 1.6 µm. Increase of feed to 0.08 mm/rev reduces the tool life to 3 km of path at Ra = 1.6 µm.

The relative wear of the cutters with was equal 7 µm/km at feed rate of 0.06 mm/rev. and 8 µm per at feed rate of 0.08 mm/rev. at 1 km cutting path.

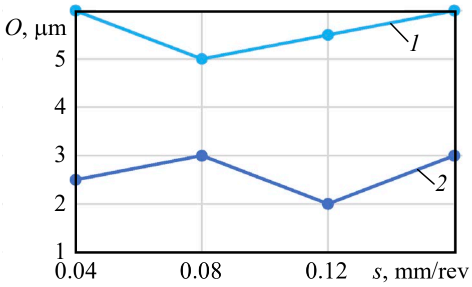

Fig. 4. Influence of feed rate on ovality *O* of holes when machining steel:
1 – single-cutter boring;
2 – double-cutter boring by feed division

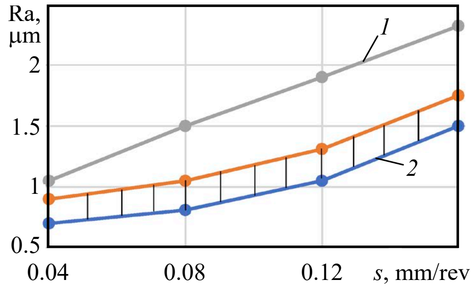

Fig. 6. Influence of feed on surface roughness when processing steel 35L: *1* – single-cutter boring; *2* – double-cutter boring by feed division; *v* = 200 m / min; *t* = 0.1 mm; *r* = 0.3 mm

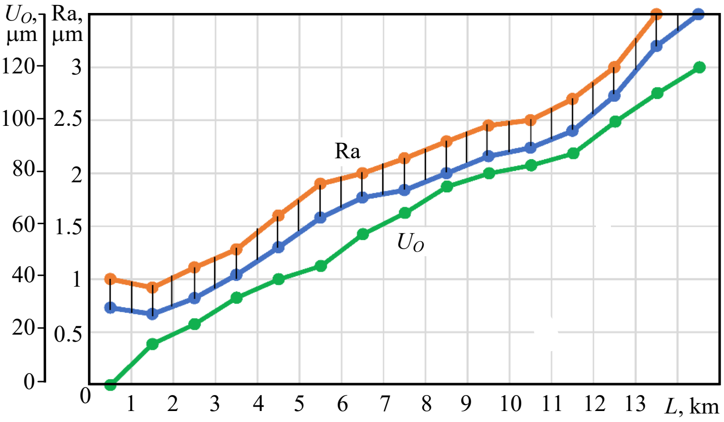

Fig. 5. *Roughness of the surface and wear of cutters during double-cutter boring of steel 35L: v = 200 m/min; s = 0.08 mm/rev; t = 0.1 mm*

The taper ratio of the holes slightly decreased with increase of feed rate, and with double-cutter boring was 1...2 µm lower comparing with single-cutter fine boring.

The ovality of the bored holes significantly decreased (Fig. 4) with double-cutter boring compared to single-cutter boring. With an increase in feed, the ovality of the holes remained practically unchanged.

Conclusions

1. Cast carbon steels can be machined with cutters made of T30K4 hard alloy, considering that surface roughness refers to 7th class only at low feed rates of 0.02...0.03 mm/rev.

2. Feed rates greater than the above values leads to a sharp increase in the relative wear of the cutters, an increase in roughness height and a significant decrease in the overall tool life.

3. For cutters made of T30K4 hard alloy, optimum cutting speed should be within the range of 200...250 m/min. An increase in the cutting speed to the indicated values is accompanied by a decrease in the relative wear of the cutters and a decrease in the height of irregularities on the machined surface. A further increase in the cutting speed leads to an increase in the temperature in the cutting zone and causes an increase in the relative wear of the cutters. In this case, the roughness of the treated surface also deteriorates.

4. The method for dividing the feed between two cutters results in decrease of feed rate when working with carbide cutters up to 0.06...0.08 mm/rev. In this case, approximately the same surface area of the parts is processed during tool life as in single-cutter boring at low feed rate. However, processing performance increases significantly.

5. The balancing of the radial components of the cutting forces in processing by feed division method leads to a significant decrease in the errors in the shape of the cross-section of the holes (ovality). Taper ratio of the bore holes reduces considerably.

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Оргіян Олександр Андрійович; Alexander Orgiyan, ORCID: https://orcid.org/0000-0002-1698-402X
Оборський Геннадій Олександрович; Gennadii Oborskyi, ORCID: https://orcid.org/0000-0002-5682-4768
Баланюк Ганна Василівна, Anna Balaniuk, ORCID: https://orcid.org/0000-0003-1628-0273
Колеснік Василь Михайлович; Vasyl Kolesnik, ORCID: https://orcid.org/0000-0002-6573-2961
Доценко Вадим Павлович, Vadym Dotsenko, ORCID: https://orcid.org/ 0000-0001-6066-2047

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