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STUDY OF THE INFLUENCE OF BASIC PROCESS PARAMETERS ON THE ROUGHNESS OF SURFACES DURING MILLING OF SCOTS PINE WOOD

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ABSTRACT

Experimental results in the processing of Scots pine (*Pinus sylvestris L.*). are presented in the paper. They were conducted under the manufacturing conditions. Three machines are used – two jointers with different knife spindle designs and with flat knives and replaceable rigid alloy plates – a helical cutter head, as well as a planer with flat knives. The measured parameter is R*z*, and an electronic profilometer was used to measure its reading. The studies were conducted using the method of planned two-factor regression analysis. The selected factors are fundamental to the milling process – feed speed v_f and radial depth of cut a_e. Their levels of variation are determined on the basis of preliminary experiments, as well as the practical possibility of their realization. The results obtained with all three machines do not exceed 45 μm, and the ones for the planer make the strongest impression.

Keywords: roughness; jointer; planer; knife spindle; solid wood; Scots pine.

INTRODUCTION

Longitudinal milling machines are widely used in companies to manufacture the furniture, doors, windows and other wood products. After cutting the rounded wood materials by frame saw, band saw, or circular saw machines and the subsequent hydrothermal treatment, their surfaces are rough, uneven, and unsuitable for furniture production without additional treatment. The first mechanical treatment, which is carried out after the primary cutting of the wood materials, is called "base forming" and is carried out on jointers. After the processing of this machine is done – most often on the side and edge, it is moved to setting the exact thickness of the wood materials. The device for this operation is called a planer. The working spindles of these machines rotate at high revolutions – from 3000 to 8000 min^{-1}- which implies that the surfaces they process will be smooth and of good quality.

When processing with milling machines, two working movements are performed – cutting and feeding. The main working movement (cutting movement) is rotational and uniform. It is performed by the cutting spindle. In the milling machines included in the present work, the feeding movement is performed by the processed material. A number of theoretical dependencies are found in the literature, which, according to the authors, allow the calculation of the roughness depending on the feed speed (Filipov 1979, Glebov 2007).

These formulas refer entirely to the depth of kinematic waves and, for simplification purposes, ignore several other factors affecting roughness.

Surface roughness is one of the main indicators that characterize the wood milling process. Apart from that, it summarizes a number of factors related to the processed material, the machine and the cutting tools, workplace conditions, the machine operator's qualification, and the kinematics of the milling process. The first factors are of such a nature that if certain norms are observed, their influence on the roughness can be minimized. The last of the mentioned factors cannot be eliminated, as it is related to the milling process and has a significant influence on the quality of the obtained surfaces. The most commonly measured parameter used to determine the roughness of milled wood surfaces is R_z, which is the arithmetic mean of the five highest protrusions and the five deepest recesses of the profile within the base length limits (Gochev, 2018; BDS EN ISO 4287:2006; BDS 4622:86). In the current study, the unevenness that occurs due to the kinematics of the milling process are of interest.

As is well known with an increase in the speed of the working movements of the longitudinal milling machines, it is clear that their productivity will also increase. However, they can increase up to a certain value. In addition, the feed speed is limited by two technological factors – the available power of the electric motor for cutting and the desired grade of roughness. A large number of experimental studies have been conducted by various researchers. Some of them study the influence of different types of treatment of the processed material, such as: chemically impregnated and thermally treated, on the roughness of the obtained surfaces with different types of woodworking machines (Chuchała, *et al.*, 2023; Korčok *et al.*, 2018; Rajko *et al.*, 2021; Adamčík *et al.*, 2022; Kvietková *et al.*, 2015). Others study the influence of wear and cutting tool construction (Dobrzyński *et al.*, 2019; Vitchev, 2019). The closest to the current research are the experimental studies related to the influence of the feed speed, the cutting speed and radial depth of cut, carried out when milling wood species widely used in furniture production. The main difference is that they were conducted under different conditions (Vitchev *et al.*, 2018; Vitchev and Gochev, 2018). However, in the literature, the author of the current study did not find comparative experimental studies regarding the influence of different designs of cutting spindles and machines on the roughness of the milled surfaces. This determines the direction of the present study. It is part of a larger one, some of whose results were already published. For example, in *Atanasov et al.* (2022) and *Atanasov et al.*, (2023), the influence of milling feed speed and radial depth of cut, the type of cutting spindle and the type of machine, on the roughness of the obtained surfaces when milling a hardwood species such as beech (*Fagus sylvatica*) and the tropical wood of meranti *(Shorea leprosula)* was studied. The research was conducted under the same conditions.

The purpose of the present study is to determine the influence of basic process parameters such as feed speed and radial depth of cut on the roughness of the obtained surfaces when processing Scots pine with different longitudinal milling machines. This also requires comparing the results between the different variants of cutting spindles and determining the range of variation of the studied factors.

MATERIAL AND METHODS

For the purposes of the experiment, two jointer machines with a different construction of the knife spindle were used – with flat knives and with helical cutterhead, as well as a planer with a knife spindle with flat knives. The more important technical parameters of the machines used and their cutting tools can be seen in Table 1.

Tab. 1 Basic parameters of machines and spindles.

№	Model	*PF415N (Italy)* www.paolonimacchine.it	*DMA 41L (Bulgaria)* www.stomana.net	*S630 (Italy)* www.steton.it
1.	Power of the motor driving the cutting mechanism, kW	3	4	5.5
2.	Maximum milling width, mm	420	410	500
3.	Diameter of the spindle, mm	110	125	110
4.	Cutting diameter, mm	113	128	113
5.	Cutting speed, $m{\cdot}s^{-1}$	32.2	31.5	30.5
6.	Number of flat blades/ *spatial screw lines	4	*3	4
7.	Sharpening angle of the cutting edges, °	40	40	40

The place for conducting the experiments is the manufacturing conditions of the companies *Vik Stroy Ltd* – town of Montana and *Pentop Ltd* – town of Varshets, whose main activities are the production of children's toys and seating furniture. Scots pine materials with a cross section of 50x50 mm and a length of 1000 mm were used as experimental samples. As is well known, although it does not have the mechanical properties of hardwood species (Sydor *et al.,* 2022)*,* its wood is widely used in furniture production. The samples were selected with a minimum number of defects. Moreover, radial lumber was used for the experiment. The density of the samples was determined by measuring the volume – with a caliper/tape measure and the mass – using an electronic scale. In addition, their moisture content was measured using a *Lignomat Tester* moisture meter (Germany, www.lignomat.de) and a contact thermometer TROTEC (Germany).

The studied factors influencing the roughness are essential to the milling process – feed speed and radial depth of cut. For the purposes of the experiment, a two-factor regression analysis was performed, and the results obtained in combinations between the factors were measured. Their levels of variation are determined on the basis of conducted preliminary experiments, as well as on the basis of the technical capabilities of the machines and the feed mechanisms used. Accordingly, $v_f \approx 5$, 10 and 15 $m{\cdot}min^{-1}$ and a_e = 1, 3, 5 mm were chosen. To implement the feeding movement in the jointer machines, a universal roller feeding mechanism is used (*HOLZ-HER, Type ETZ,* Germany) which can feed the materials at a theoretical speed of 2, 4, 5, 6, 10, 12, 15 and 30 $m{\cdot}min^{-1}$.

During the experiment, the temperature and humidity of the working premises were also measured using the device *MASTECH MS 6300* (China), because, although to a lesser extent, they influence the studied parameter. In addition, immediately before the start of the experiments, the flat knives of the machines were sharpened, and the cutting edges of the helical cutterhead were replaced.

The roughness of the milled surfaces is determined according to the standards BDS 4622: 86 and BDS EN ISO 4287:2006, through the parameter R_z. Its values were measured by profilometer *SJ-210, Mitutoyo*, Japan, whose general view can be seen in Figure 1. Its settings are: profile – *R*, profile filter – Gauss, number of sampling lengths *n*=6; evaluation length *ln*=15 mm, cut-off length λc=2.5 mm, λs=8 µm, measuring speed 0.25 $mm{\cdot}s^{-1}$.

Fig. 1 General view of profilometer *SJ-210, Mitutoyo* (Japan), www.mitutoyo.eu.

The software products *QstatLab5* and *Microsoft Excel* were used for the processing of the results. The experimental matrix is presented in Table 2. It shows the combinations between the factors in explicit and coded form. It is also noted that in order to make the results more reliable, the experiments with the average values of the variation levels of the factors $v_f \approx 10$ m·min^{-1} and $a_e = 3$ mm were conducted five times.

Tab. 2 Experimental Matrix.

№	v_f, m·min^{-1}	x_1	a_e, mm	x_2
1.	15	+1	5	+1
2.	15	+1	1	–1
3.	5	–1	5	+1
4.	5	–1	1	–1
5.	10	0	3	0
6.	10	0	5	+1
7.	15	+1	3	0
8.	10	0	1	–1
9.	5	–1	3	0
10.	10	0	3	0
11.	10	0	3	0
12.	10	0	3	0
13.	10	0	3	0
14.	10	0	3	0

RESULTS AND DISCUSSION

The average results of measurements for moisture content and density of test samples are φ=12% and ρ=450 kg·m^{-3}. The average values of relative humidity and temperature in the workshops are $\varphi_w \approx 55$ % and $t \approx 19 \div 20$ ˚C. It means that the conditions for performing the experiment will not adversely affect the results of the study. The resulting regression equations after processing with the software product mentioned above are as follows:

PF415N: $Rz=25.166+7.293v_f+2.862a_e+4.818v_f^{\,2}-0.311a_e^2+2.807v_fa_e$; (1)

DMA41L: $Rz=23.301+4.963v_f+3.716a_e+3.144v_f^2-2.470a_e^2+2.713v_fa_e$; (2)

S630: $Rz=25.045+3.419v_f+0.354a_e+1.027v_f^2-3.489a_e^2-1.343v_fa_e$. (3)

When comparing the calculated value of F_c – Fisher's criterion with the critical one (F_{cr} – 9.01), used for verification, it becomes clear that the models are adequate, and the resulting equations can be used to describe the relevant processes. All equations show that the regression coefficient in front x_1 is more significant than that in front x_2. This means that the feed speed factor has a more significant influence on the studied quantity R_z – the roughness of the obtained surfaces. In addition, the symbol in front of the two studied parameters is "+", which means that as the levels of variation of x_1 and x_2 increase, the roughness will also increase. Although radial depths of cut are not directly involved in wave formations due to the kinematics of the process but from the derived regression equations, it is observed that, although to a lesser extent, they have an effect on the roughness.

Figure 2 shows the effect of feed speed when machining with the jointer *PF415N* at the three radial depths of cut. The blue curve refers to a_e = 3 mm. It can be seen that at the lower values of the feed speed v_f (from 5 to 8 m·min^{-1}) the roughness R_z is approximately 22.7 µm. After exceeding 10 m·min^{-1} the roughness starts to increase more intensively and at a feed speed of 15 m·min^{-1} it reaches its maximum of 37.3 µm. Thus, the difference in roughness between the initial and final feed rates is approximately 15 µm. This shows that at lower values of the feed speed, it has a minimal effect on the quality of the machined surfaces, after which it starts to change more intensively. This trend is also observed for the other studied radial depths of cut. As the radial depth of cut, the roughness also increases is probably the different chip separation when the cutting edges penetrate deeper into the wood, as well as the increase in cutting forces. Overall, the figure shows that at the lowest feed speeds, the radial depths of the cut have practically no effect on the roughness. At all three levels of x_2 variation, the roughness barely changes up to a feed speed of about 7.5 m·min^{-1}. Subsequently, it increases, and this tendency is most sharply observed at a radial depth of cut of 5 mm. The maximum roughness value obtained is 42.6 µm at a value of x_1 – 15 m·min^{-1} and x_2 – 5 mm, respectively.

Figure 3 shows the influence of the radial depth of cut on the surface roughness when processing Scots pine with the jointer *PF415N* at an average feed speed (v_f = 10 m.mim^{-1}). It is also observed that the radial depth of the cut factor has significantly less influence on the surface roughness, especially at the lower values. This is confirmed by the regression equations as well – the coefficient in front of the second factor is smaller than that in front of the first. At the low values of radial depth of cut, the roughness is approximately 22 µm, and the maximum value obtained at the highest radial depth of cut is 27.7 µm. In contrast to the previously discussed factor, in the case of radial depth of cut, a more intense increase in roughness with its increase is not noticed.

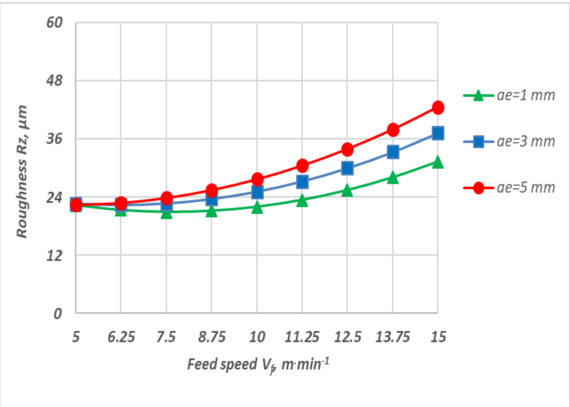

Fig. 2 Effects of feed speed on surface roughness at different radial depths of cut when machining Scots pine with jointer *PF415N*.

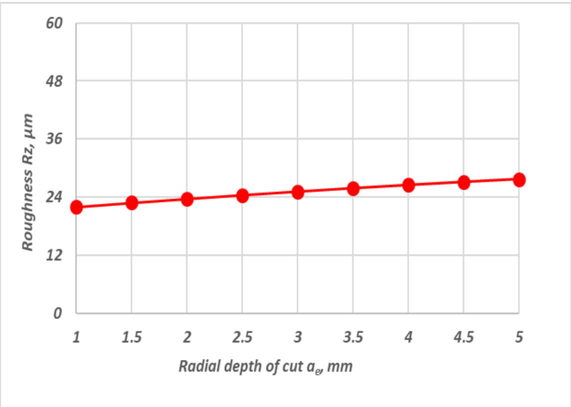

Fig. 3 Effects of radial depth of cut on surface roughness in longitudinal milling of Scots pine with jointer *PF415N*.

Figure 4 graphically presents the effect of feed speed on roughness (at a_e=3mm), when milling Scots pine with the jointer *DMA 41L* with helical cutterhead. As it is known from practice, the surfaces obtained after processing with the machines with knife spindles with such a construction are of better quality. In addition, the load on the cutting spindle in these machines is less. The main reason is that with helical knife spindle, the cutting of the wood grains, depending on the movement and the cutting edge, is 90°-90°, 0°-90°, 90°-0°, while with those with flat knives, it is 90°-90°, 90°-0°. The statement is also confirmed by the figure, in which the curve does not exceed that of the flat knives machine along its entire length.

In contrast to the studied jointer machines, with the planer, the feed speed does not have a significant influence on the roughness of the obtained surfaces when processing Scots pine. This is also clearly seen in Figure 5. The difference in the roughness between speed 5 and 15 m·min^{-1} is less than 7 μm. The main reason for this is the way in which the feed force is conducted, which is frictional – i.e., it is carried out by pressing with a particular force. In addition, there is a methodology in the literature for determining the pressing force, which is more significant for the feed roller after the knife spindle (Vlasev, 2007). For example, if we assume that the cutting forces (*Fc* – tangential and *Fr* – radial) *Fc* = 50 N and *Fr* = 30 N, as well as the values indicated in the literature for the forces with which the wood is affected by the pressing beams, friction coefficients, we will get that the pressing from the rear roller is with a force of more than 700 N. This means that when passing through the rear feed roller, some of the micro-uniformities are smoothed out, and some of the resulting deformations are plastic, while others are elastic. It is precisely due to the elastic deformations that the roughness increases as the feed speed increases. However, although with minimal differences, its values do not exceed those of the jointer with the spindle with flat knives. During the conduct of the experimental studies, a variant with feeding the part by pushing was also tested. In this way, relatively equal results were obtained with those of the jointer with flat knives. But in practice, with all planers, the feeding movement is based on a frictional principle. For this reason, the entire series of tests was carried out, although the final roughness will differ from that obtained immediately after the knife shaft. In addition, the tested machine does not have a rear pressure beam – i.e., only the rear feed roller has an influence after the knife spindle.

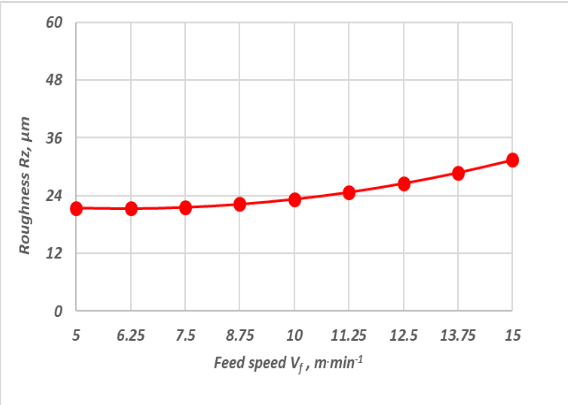

Fig. 4 Effects of feed speed on surface roughness in longitudinal milling of Scots pine with jointer *DMA41L*.

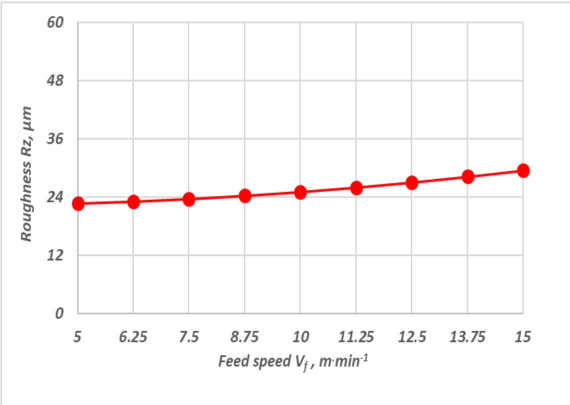

Fig. 5 Effects of feed speed on surface roughness in longitudinal milling of Scots pine with planer *S630*.

The next two Figures show results for the influence of the studied factors on the roughness of the surfaces for all three machines examined. Figure 6 shows the effect of feed speed when milling Scots pine with different milling machines at maximum radial depth of cut, and Figure 7 shows the effect of radial depth of cut on roughness when machining Scots pine at the highest feed speed. From the first graph, it is clear that the green curve, which refers to the planer, has the lowest roughness of the milled surfaces. As mentioned, after the knife spindle, the rear feed roller presses the machined surface, which further smoothes it. When comparing the results of the two jointers, it can be seen that the roughness of the one with the helical cutterhead has lower values. Furthermore, it is known from theory that with larger cutting radii, the depth of the kinematic waves should have lower values. In the studied machines, the cutting radius parameter is bigger in the machine *DMA41L*.

In relation to the less important factor (a_e) when operating with the planer, it seems that there is practically no connection between the radial depth of cut and the roughness during processing. However, the regression coefficient before x_2 in equation 3 has a positive sign. It means that, in general, as the milling thickness a_e increases, there is also a certain increase in the roughness.

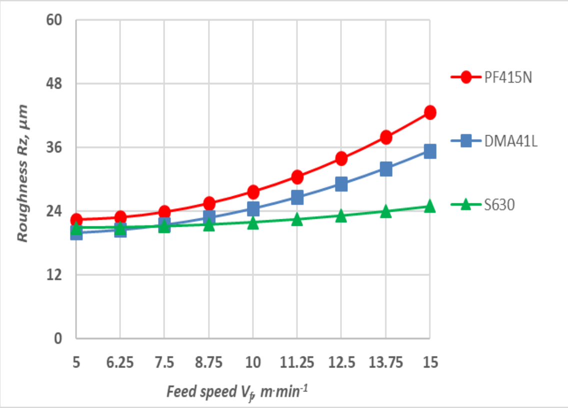

Fig. 6 Effects of feed speed on surface roughness in longitudinal milling of Scots pine with different milling machines.

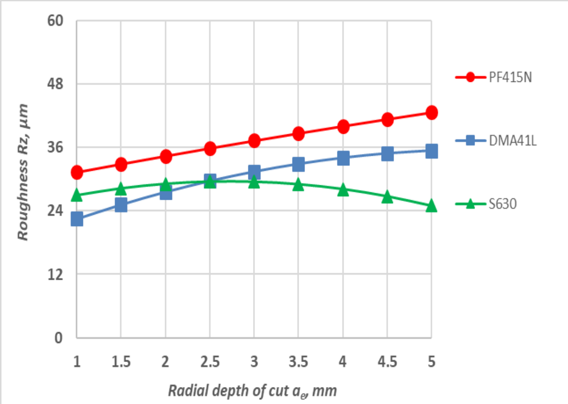

Fig. 7 Effects of radial depth of cut on surface roughness in longitudinal milling of Scots pine with different milling machines.

The results presented above are obtained on the basis of a large number of experimental studies carried out in manufacturing conditions. When we compare those for the jointer with flat knives and calculate the magnitude of the kinematic waves, it is noticed that the difference between the obtained roughness and calculated values for the kinematic waves varies approximately ten to twenty times. This means that the formula proposed by the authors mentioned in the introduction is not very suitable for practical roughness prediction (determined by the parameter R_z), as results show that factors unrelated to the kinematics of the cutting process also have a significant impact on the final roughness.

Comparing the results with the studies of other authors is not very correct, since the conditions of the experiments, the materials used, the machines and their cutting mechanisms are different. As all this would lead to inconsistency. For example, in *Vichev and Gochev* (2018), the influence of cutting and feeding speeds, as well as uncut chip thickness, are studied, but two of the factors had different levels of variation, and the machine studied is a wood shaper. Other similar experimental studies can be found in the literature. In *Vitchev et al.* (2021) the influence of feed speed and radial depth of cut when processing linden (*Tilia Sp.*) with a helical cutterhead jointer is studied. The results confirm that feed speed has a more significant influence on the roughness than the radial depth of the cut. In addition, the obtained values for processing quality for linden are slightly higher than those for the considered wood species. The reason for this is the different conditions for the experiment. Mainly in the different physico-mechanical parameters of the respective wood, the cutting speed and the diameter of the knife spindle.

Comparing the roughness of different wood species is not very correct, as their physico-mechanical properties are different. Even the same type of wood, grown under other conditions, may have different densities, compressive strength, bending strength, shear strength, etc. The elastic and plastic deformations are different, as well as the strength limit of wood fibers (Gochev 2018). When comparing the results with those carried out at the same levels of variation of the studied factors, but in the processing of beech (Atanasov *et al.*, 2022), it is noticed that the tendency is a deterioration of the quality with an increase in the density of the wood. This is slightly contrary to the expected results, since when cutting hardwood, due to its higher resistance, cracks are expected to be less. The main reason for the worse results can be found in the faster wear of the cutting edges of the tools.

CONCLUSIONS

Based on the experimental studies, the following conclusions and recommendations can be made when processing Scots pine with longitudinal milling machines:

1. For planers, it has been proven that pressing the workpiece after the knife spindle has a beneficial effect on the roughness. When calculating with actual values of forces, according to the presented methodology for force calculation of planers, it became clear that the required pressing force from the rear feed roller exceeds 700 N. This means that some of the micro-uniformities that occur during processing are plastically deformed and smoothed out. However, to a lesser extent, a tendency is observed that as the feed speed and radial depth of cut increase, the roughness class deteriorates – i.e., there are also elastic deformations of the surface of the wood materials. This allows planer machines, from a performance standpoint, to be designed with feed mechanisms that can realize a higher feed speed.

2. The roughness results show that at the highest levels of variation of the factors studied, the roughness when milling Scots pine rarely exceeds 40 μm. This means that, from the point of view of the roughness class, a feed speed of over 15 $m \cdot min^{-1}$ is possible. During preliminary tests, however, it was found that when the feed speed exceeded 20 $m \cdot min^{-1}$, the operation of the machine became a difficult task. This gives reason to recommend that the maximum feed speed for longitudinal milling machines should not exceed 20 $m \cdot min^{-1}$. The lower limit of the feed speed is good to start from 5 $m \cdot min^{-1}$, because below it the differences in the results are minimal and besides, productivity is low. Of course, these values are recommended and can be exceeded, but this will certainly lead to difficulties with the servicing of the machine in time.

3. Theoretical dependencies that are found in the literature refer to the depth of the waves as a consequence of the kinematic nature of the milling process. In addition, they are valid subject to a number of conditions. However, the roughness of the resulting surfaces also depends on a number of other factors. This makes them practically difficult to apply. It should not be forgotten that woodworking machines are designed to work in manufacturing, not laboratory conditions. This means that it is recommended to use equations derived from many experimental studies, such as those presented in this paper, to roughly precalculate the roughness.

4. Helical cutter heads are also recommended for constructing the cutting mechanisms of modern longitudinal milling machines. The roughness results for them are better. It means that the feed speed and, hence, the productivity can be higher.

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