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AESTHETIC PROPERTIES AND QUALITY OF RELIEF SURFACES OF WOODEN PRODUCTS IN AUTOMATED MANUFACTURING

Mikhail Chernykh – Polina Ostanina – Vladimir Stollmann

ABSTRACT

The components of surface quality of relief artistic-industrial wooden products processed on CNC machines are presented in the paper. The labour intensity and machining cost with further relief manual finish of typical products are compared. The functional dependencies of labour intensity and machining cost on the mill cross feed step were found and the availability of its rational values minimizing the total labour intensity of machining and manual finish and total machining costs of and finish are provided.

Key words: automated manufacturing, 3D-milling, wood, CNC machines, labor intensity, cost.

INTRODUCTION

Automated manufacturing of artistic-industrial wooden products is intensively developing (CHERNYKH 2007, 2008, RUDENKO 2011, SADYKOVA 2014, STAVROS 2018), it is cost efficient even with small product batches (several pieces) (CHERNYKH 2008). A number of advantages is provided in comparison with manual carving: high productivity and accuracy, vast opportunities of scaling and transforming, repeatability and identity of the elements, use of previously developed software libraries, operative adjustment of supervisor program, etc (DZURENDA 2008).

The quality of product surface in automated manufacturing depends on the quality of 3D-model, machining strategy, milling mode elements, tool and workpiece quality (Fig. 1).

The low quality of 3D-model can result in distortion of the surface relief and simplification of its shape in comparison with the prototype, formation of unplanned point defects (holes) on the product surface.

Irregularities observed on the product surface after finishing 3D-milling can be divided into systemic and chaotic. Crests technologically inevitable during finish milling due to the spherical shape of the mill cutting edge can be referred to systemic irregularities (Fig. 2), and irregularities of destruction – shears on the product edges and sides, tearing out and wooly grains – to chaotic ones. Systemic irregularities can be predicted, but it is impossible with chaotic ones. Apart from the irregularities indicated, the scuff is formed on the product surface from the cut in wood grains, and non-milled areas are possible in sharp corners and points of the product surface matching (BRENCI 2006, SALCA 2008).

The irregularities of destruction can be minimized or completely eliminated if using high-quality workpieces, selecting the rational machining strategy and milling mode elements, and systemic ones can only be minimized, their complete elimination requires manual finish of the product.

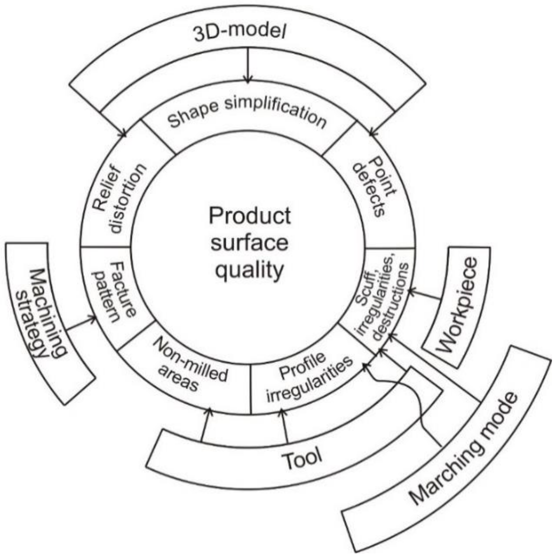
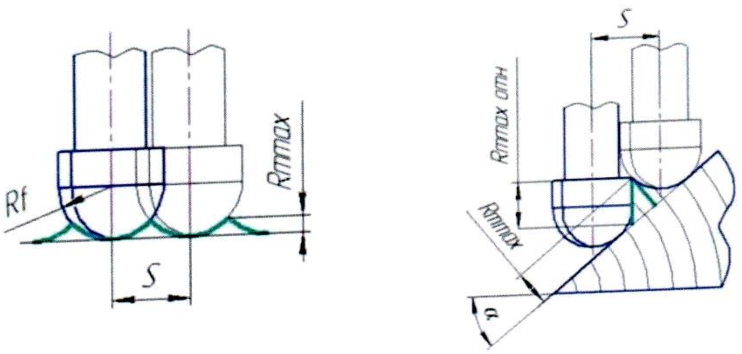


Fig. 1 Components of surface quality of wooden product with CNC machining and their connection with design-manufacturing factors.



a) b)

Fig. 2 Profile irregularities of the flat (a) and inclined (b) surfaces after finishing 3D-milling (CHERNYKH 2013).

Gloss is an important aesthetic indicator of artistic-industrial products. It should be pointed out that even a flat and smooth facture of wooden products after the finishing CNC-machining with small step S of the mill cross feed will have matte gloss due to crests and scuff. The manual finish is required to enhance the gloss and prepare the surface for paint-and-lacquer coating, as a minimum, grinding with sandpaper, and if there are non-milled areas – manual carving.

When designing the technological processes, the information about the rational ratios between the labor intensity of machining and manual finish and their cost is necessary (SIKLIENKA 2016, KMINIAK 2017).

MATERIALS AND METHODS

The investigation was carried out on typical products (samples) with projected and hollow relief produced from the popular wood species – beech, oak, pine. The workpieces did not have knots and cross-grained grains. The products dimensions are given in Figs. 3

and 4. 50 samples of each type were produced from beechwood, 15 – from oak and pine each.

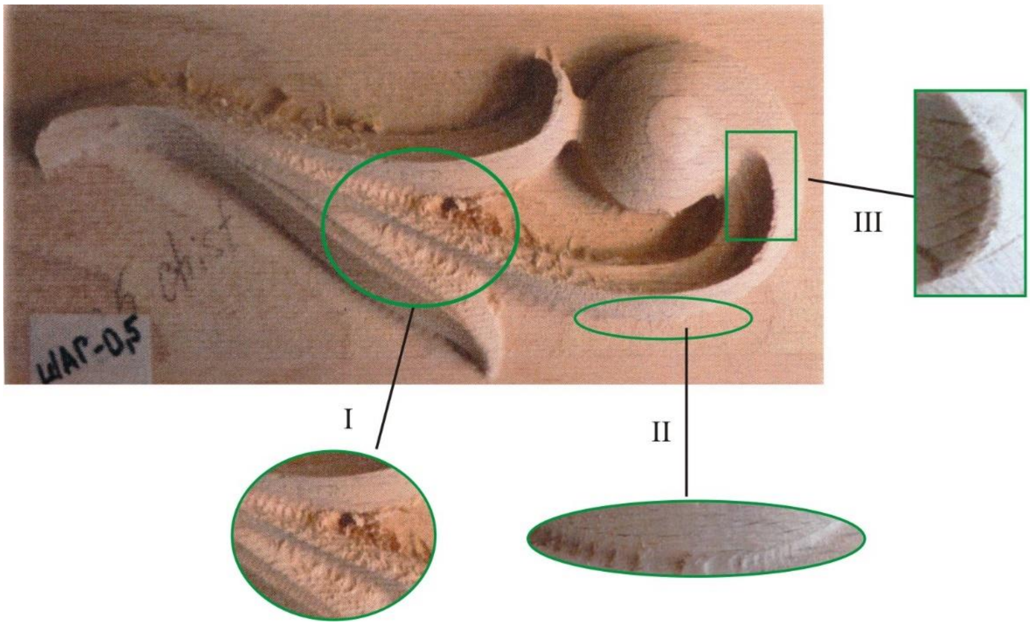


Fig. 3 Product "decorative molding" after finishing 3D-milling with non-milled areas in sharp corners, tearing out and wooly grains (I), non-milled areas in the spots of relief and background matching (II) and shears on edges (III); beechwood, planned dimensions – 80 × 150mm, the maximum relief height – 12 mm, longitudinal direction of wood grains, raster strategy of processing, feed – along the grains.

Fig. 4 Product "rose" after finishing 3D-milling and manual finish; beechwood, planned dimensions – 80 × 80 mm (a), the maximum relief height – 25 mm.

The samples were produced by milling on machining center GFY 98/108-SW. The roughing was performed with 8-mm cylindrical carbide mills, finishing – with 8-mm carbide mills with spherical butt end at spindle speed of 14,000 rpm. Longitudinal feed S_{long} was 1.2 m/min. Step of the mill cross feed S, determining the distance between the crests, was selected based on the following considerations.

The influence of parameters of irregularities profile onto human organoleptic perception of the product surface is manifested differently. Step S of the crests has the main influence on visual perception, while their height $Rm_{max.}$ – on the tactile one. The product surface can be visually perceived as flat smooth, flat rough or relief (OSTANINA 2012, PONOMAREVA 2014), as well as comfortable or uncomfortable at tactile contact (OSTANINA 2014).

The rational value of S depends on the perception of product surface facture implied by the designer. In general, the surface is visually perceived as flat smooth, if step S is less than minimal extension E of vividly distinguished light-to-dark transition zones (OSTANINA 2012), flat rough, if $2E \leq S \leq 3E$, and relief, when $S \geq 4E$ (SOKOLOVA *et al*. 2013). In the range $E < S < 2E$ the facture is visually perceived as intermediary between flat smooth and flat rough, and in the range $3E < S < 4E$ – as intermediary between flat rough and relief. Since in manufacturing step S is technologically conditioned by the productivity and is in the range between 0.1 and 2.0 mm, the product surface after finish milling, depending on a certain step value, is perceived as either relief or intermediary between them, and step S in the investigation was changed from 0.1 up to 2.0 mm.

Height of the crests Rm_{max} was measured with the contact profilometer model 130, degree of precision 1, company Proton Miet Moscow, Russia. The manual finish was performed by a professional carver, after milling the relief was ground with sandpaper, and non-milled sharp internal corners – with a cutter.

The milling and finishing time was measured with a stopwatch.

RESULTS AND DISCUSSION

The scuff was observed on all products after the finish milling, non-milled areas in sharp corners and in the spots of relief and background matching, and on some products – tearing out, wooly grains, shears on edges (Fig. 3). All defects were eliminated by manual finish, there were no non-eliminated defects on the products.

The labor intensity of machining and manual processing depend on cross feed step S. With the step increase the time of machining goes down and the time of further manual finish increases (Fig. 4). At some value S_{PT} of step S the total processing time $T_{\sum}$ of the product is minimal. The minimum availability allows, depending on certain manufacturing conditions, optimizing the production process by the time periods of product batch manufacturing and (or) production costs. The rational value of cross feed step S_{PT}, corresponding to the least total processing time, depends on the product geometry – its shape, relief height, relief location against the background (projected or hollow relief) and other peculiarities.

When the product, e.g., “rose” (Fig. 3) has internal corner areas hardly accessible for manual finish, the increase of step S sharply extends the time of manual finish, therefore, the minimum of total time function $T_{\sum}$ corresponds to small values of step S. For the product “rose” S_{PT} is about 0.3 mm.

The increased width of relief cavities facilitates the manual finish, decreases the time required for it and total processing time $T_{\sum}$. Thus, the manual finish of “decorative molding” takes 4–5 times less time than “rose”, and minimum of the total time function shifts to the step average values. The value of S_{PT} is about 0.5 mm.

The decrease in the relief height with the same pattern and dimensions results in the decrease in both components of total processing time $T_{\sum}$ (machining and manual), and minimum of its function $T_{\sum} = f(S)$ shifts to greater values of step S. For instance, with the decrease in the relief height of “decorative molding” from 12 to 6 mm the total processing time decreases by approximately 30%, and the function minimum is observed with the value of S_{PT} equaling about 1.6 mm (Fig. 5).

The costs of finish milling and manual finishing, as well as the processing time, depend on the selected value of step S. Since the cost of one machine-hour of CNC machining is from 500 up to 1000 rubles (CHERNYKH 2009) and exceeds the cost of one hour of manual finish in several times, the minimal values of total processing cost function $C_{\sum}$ (machining and manual) shift relative to the minimal values of total processing time $T_{\sum}$ to greater values of step S. Thus, for the product "rose" the minimum of function $T_\Sigma = f_1(S)$ occurs at $S_{PT} \approx 0.3$ mm, and the minimum of function $C_\Sigma = f_2(S)$ – at $S_{PC} \approx 0.6$ mm (Fig. 4).

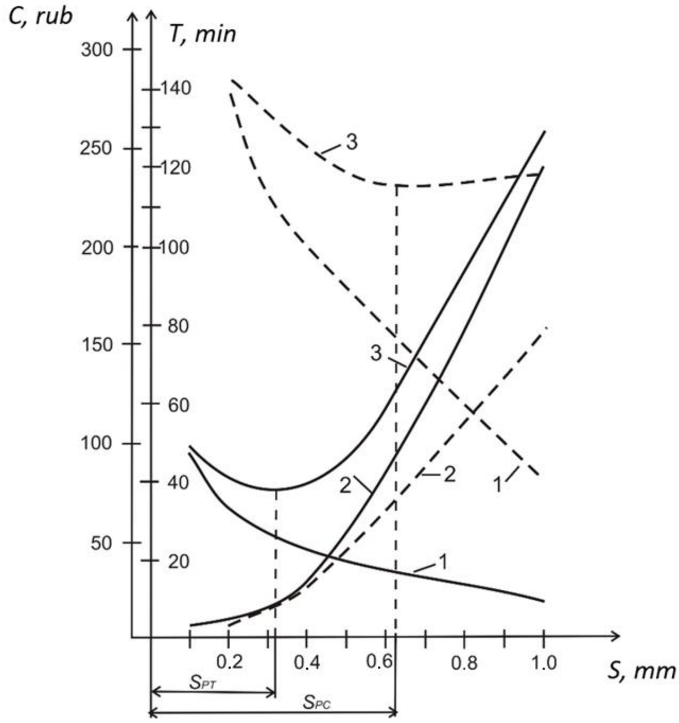


Fig. 5 Dependence of time T (solid lines) and cost C (dotted lines) of processing the product "rose" (Fig. 4) on the mill cross feed step S: 1 – machining; 2 – manual finish; 3 – total time and cost.

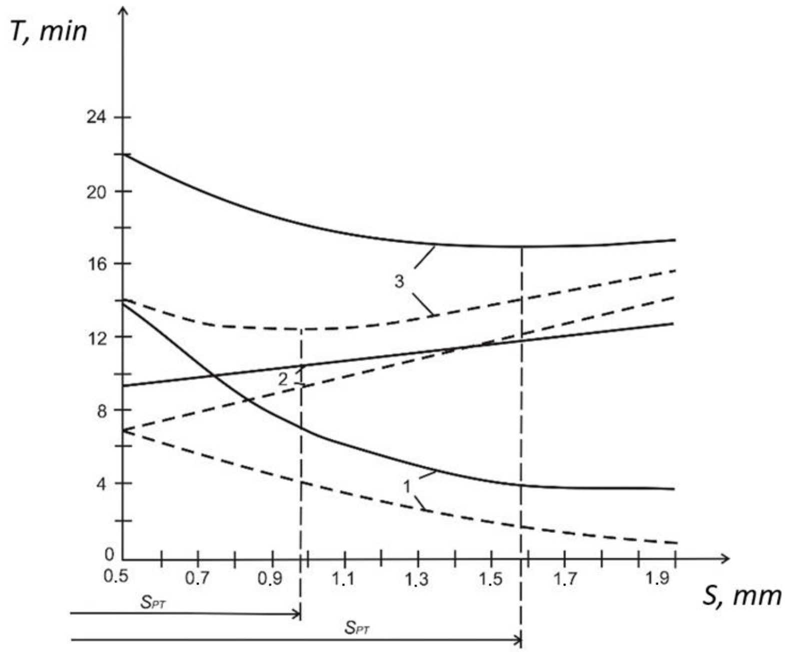


Fig. 6 Dependencies of the processing time of the product "decorative molding" (Fig. 3) with projected (solid lines) and hollow (dotted lines) relief on the mill cross feed step *S*: 1 – machining time, 2 – manual finish time, 3 – total time. The greatest height (depth) of relief is 6 mm, the planned product dimensions – 80 × 150 mm, beechwood.

Let us point out that the total processing cost of the product "rose" in the range of steps $0.5<S<0.9$ mm does not practically depend on the step value. Taking into account that with the step decrease the thickness of the wood cut layer goes down and the possibility of formation of tearing out and shears diminishes, it is advisable, in such cases, to select a smaller step to achieve better product quality and form a higher selling price.

Some manufacturers of artistic-industrial wooden products successfully use the following regulator. Thus, depending on the surface processing quality, the company "Stavros" (Saint Petersburg) offers three price categories of products – economy, prestige and VIP. The price of products in the second category is 1.3–1.5 times, and in the third one – in 2.0–2.5 times higher than in the first category (STAVROS 2018).

The irregularities of destruction determining the product surface quality after machining – wooly grains, tearing out, shears – depend on the wood species, cut type, geometry and location of the relief relative to the grains, processing strategy and milling mode elements.

Since the methodology of instrumentation determination of irregularities of destruction is not available, it is proposed to use their relative area to evaluate the quality of the processed surface (CHERNYKH 2009)

$$k = \frac{F_p}{F_u} \times 100\% ,$$

where k – coefficient characterizing the relative area of the irregularities of destruction, %;
F_p – product area occupied by the irregularities of destruction;
F_u – area of the milled product surface.

Out of the wood species, the highest quality is achieved when milling beechwood, which has a fine uniform structure. The quality of processed surfaces of oak is lower due to the availability of large vessels, increased hardness and brittleness of its timber, the quality of pine is still lower due to its inclination to shearing (Table) (CHERNYKH 2009).

Tab. 1 Values of quality indicators of the product surface quality after finishing 3D-milling.

Indicator	Species		
	Pine	Oak	Beech
Rm_{max}, mcm	34.2	33.1	22.5
k, %	11.5	10.6	8.6

Apart from the wood species, the value of coefficient k, i.e. processing quality, is influenced by its wetness, cut type, direction of the mill feed against the grains, state of its cutting edges, values of milling mode elements.

As it is known, the processed surface quality diminishes with the wetness increase. It is better to use the radial wood cut, since the scuff is more visible on the tangential cut, thus worsening the product appearance and increasing the manual processing labor intensity, and the tearing out becomes more possible. The area of regions with irregularities of destruction F_d during milling along the grains is significantly smaller than during milling against the grains. When processing against the grains, the possibility of shearing small elements and sharp ridges of the relief becomes greater. Therefore, the elongated images and ornaments should be located along the grains as demonstrated in Fig. 3. However, when milling along the grains, they are getting split, more scuff and tearing are formed.

With the increased mill feed speed the number and sizes of the irregularities of destruction increase, but the machining labor intensity goes down, however, not always proportionally to the speed increase. Thus, when the regions with sharp drops of relief are present in the product, the increase in the feed speed, starting from some value, does not result in the reduced product processing time due to the necessity of braking and accelerating the machine drive on the regions of relief drops, and the area of the irregularities of destruction increases (CHERNYKH 2009).

CONCLUSION

Aesthetic properties and quality of the surface of relief wooden products in automated manufacturing depends on a number of design-manufacturing factors – quality of 3D model, processing strategy, elements of milling mode, quality of tools and workpieces.

Irregularities observed on the product surface after 3D-processing can be divided into systemic and chaotic. Systemic irregularities have the appearance of crests formed due to the spherical shape of the mill.

To improve the aesthetic properties and quality of relief wooden products obtained by milling on CNC machines, the manual finish is required. Even with the small height of relief (6 mm) the time of manual finish is comparable with the machining time.

The time of machining and manual finish mainly depends on mill cross feed step *S*, the machining time decreases with its increase, on the contrary, the manual finish time increases.

The availability of rational value S_{PT} of step *S*, minimizing total time $T_{\sum}$ of the product machining and manual processing was found. With the increased relief height and its complexity the volume of manual finish and share of manual time in total processing time $T_{\sum}$ go up, and the rational value of step S_{PT} shifts to small values of cross feed step *S*.

The availability of rational value of step S_{PC}, minimizing total costs $C_{\sum}$ for machining and manual finish was also found. In general, the values S_{PT} and S_{PC} do not coincide, which enables a manufacturer to optimize the processing technological process either by time of fulfilling the order or by manufacturing costs depending on the delivery conditions of the products. If the cost of one machine-hour exceeds one working hour of a carver, the value of S_{PC} exceeds S_{PT}.

The indicator characterizing the ratio of the area of irregularities of destruction to the milled area of the product surface can serve as the criterion of integrated quality evaluation of product surface after finishing CNC-milling.

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AUTHORS‘ ADDRESSES

Prof. Chernykh Mikhail Mikhailovich, Doctor of Technical Sciences
Izhevsk state technical university of the name M.T. Kalashnikov
Faculty of Advertising and Design
Department of Technology of industrial and artistic processing of materials
7 Studencheskaya street
426069 Izhevsk
Russia
rid@istu.ru

Ostanina Polina Aleksandrovna, Phd, assistant professor
Izhevsk state technical university of the name M.T. Kalashnikov
Department of Technology of industrial and artistic processing of materials
7 Studencheskaya street
426069 Izhevsk
Russia
pollyost@yandex.ru

Vladimir Stollmann, CSc. PhD., assistant professor
Technical university in Zvolen
Faculty of Forestry
Department of Forest Harvesting, Logistics and Amelioration
Masarykova 24
960 53 Zvolen
Slovakia
stollmannv@tuzvo.sk