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ANALYSIS OF DIMENSIONAL ACCURACY OF MDF MILLING PROCESS

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ABSTRACT

The aim of this paper was to present the experimental study of MDF milling process's dimensional accuracy conducted by means of standard CNC router. The analysis of long- and short-term's machining accuracy was based on ISO 21747 2006 study involved the side milling and grooving processes. It turned out that the significant tool wear can reduce a machining accuracy from IT12 to IT17 (ISO 286 2010) and for an adequate reaction to the progression of tool wear it is a workpiece rather than a tool which should be measured (monitoring of decrease in cutting diameter can be useless when side milling process is involved).

KEYWORDS: Dimensional accuracy, MDF milling, CNC router.

INTRODUCTION

Medium density fiberboard (MDF) is an industrially manufactured wood-based material, which is commonly used in a large-scale production of furniture, interior fitments, shop fitting and many other similar products. The well known advantages of MDF are dimension stability and high level of machinability (Gaitonde et al. 2008). The uniform structure of MDF allows for very precise machining (Aguilera 2010). The furniture components made of MDF are frequently manufactured with the use of milling machines (for example CNC routers). Therefore some basic aspects of MDF milling process (cutting forces, tool wear, surface roughness, burr formation, machining accuracy etc.) have been studied and discussed in the specialist scientific literature (Aguilera et al. 2000, Ohuchi and Murase 2001, 2005, 2006, Ohuchi et al. 2008, Davim et al. 2009). The advanced analysis of dimensional accuracy of MDF milling process led even to the development of automatic, adaptive control grooving system corresponding to progression of tool wear (Ohuchi and Murase 2006). The development of such system is essential since the long-term maintaining of low level of cutting errors is a very important problem.

The quality capability of manufacturing processes in any industrial sectors can be analyzed by means of standard engineering statistical methods. Statistical Process Control (SPC) - a well known way of quality control - can be effectively implemented also in the forest products industry or wood products manufacturing (Mannes et al. 2002, 2003, 2004, Staudhammer et al. 2005, 2006, 2007, Young and Winistorfer 1999, Yuong et al. 1999, 2007). The application of adequate statistical methods can lead to gaining detailed knowledge about the manufacturing process, especially better understanding of the process variation's causes. Such knowledge is usually necessary for more efficient process controlling. There are a lot of standards (general or industry-specific, international or national etc.) which were intended for the analysis of production process quality. Unfortunately, most of them require stationarity of a process and normal distribution of quality characteristic of a product. This is a serious limitation of their adequate applicability. However one of the international standards can be used for "very differently shaped distributions with respect to time" (ISO 21747 2006).

Truly useful analysis of a dimensional accuracy of any machining process must be based on precisely adequate for a particular industry, formal, criteria of accuracy. In some European countries there are national standards containing fit and tolerance systems, which are officially recommended for the use in furniture production. It is worth noting that almost all these industry-specific standards coincide, to some extent, with ISO 286 2010 - well known and commonly used geometrical product specification (GPS) standard (Laszewicz and Górski 2010). The ISO 286 2010 standard defines the international tolerance (IT) grades i.e. standardized tolerances to be used for linear sizes. The IT12 ÷ IT18 grades (the so-called "large manufacturing tolerances) can be regarded as a formal, international reference system for the analysis of dimensional accuracy of any furniture components, including components made of MDF (Laszewicz and Górski 2010).

The aim of this paper is to present the experimental study of MDF milling process's dimensional accuracy conducted by means of standard CNC router. The analysis of long- and short-term's machining accuracy was based on international standard ISO 21747 2006.

MATERIAL AND METHODS

The machined material, commercial MDF, was supplied by two well-known on the global market manufacturers. Therefore, the additional marking of the material was introduced: MDF-1/MDF-2. Such distinction was reasonable due to some differences between MDF-1's and MDF-2's properties (Tab. 1). The machining process was done by means of standard CNC milling machine (Busellato JET 130). The milling cutter was a typical carbide tipped end mill (DIMAR HM Dynamic, number of teeth: 2, nominal diameter: 12 mm, length of working part: 51 mm, tool rake angle: 15°, tool clearance angle: 15°).

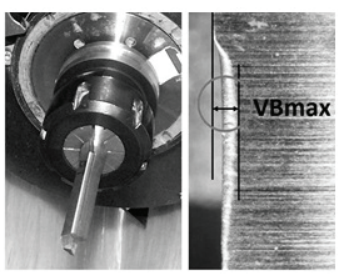

Fig. 1: General view of the end mill and tool wear indicator (VBmax).

The study was carried out for each of twelve variants of cutting conditions defined in Tab. 2. The tool remained the same during the whole experiment and only the cutting parameters were periodically changed. Tool wear monitoring was done with the use of workshop microscope. The maximum value of flank wear (VBmax) was a tool wear indicator (Fig. 1).

Tab. 1: Some mechanical and physical properties of MDF-1 and MDF-2.

Material	Density (kg.m^{-3})	Tensile strength (MPa)	Swelling after 24 h (%)	Flexural strength	Modulus of elasticity
				(MPa)	
MDF-1	740	0.57	8	40	4020
MDF-2	760	0.42	22	35	4050

Tab. 2: Twelve cutting conditions variants used in the experiments.

Name of cutting conditions variant	Characteristic of variant		
	Feed per tooth	Material	Clamping
Variant 01	0.2 mm	MDF-1	Vacuum
Variant 02	0.2 mm	MDF-2	Vacuum
Variant 03	0.4 mm	MDF-1	Vacuum
Variant 04	0.4 mm	MDF-2	Vacuum
Variant 05	0.6 mm	MDF-1	Vacuum
Variant 06	0.6 mm	MDF-2	Vacuum
Variant 07	0.2 mm	MDF-1	Screws
Variant 08	0.2 mm	MDF-2	Screws
Variant 09	0.4 mm	MDF-1	Screws
Variant 10	0.4 mm	MDF-2	Screws
Variant 11	0.6 mm	MDF-1	Screws
Variant 12	0.6 mm	MDF-2	Screws

The study involved the side milling and grooving processes. The final results of the total, multipass milling process were three dimensions of the workpiece: ”A” - width of the rabbet, ”B” - width of the first groove and ”C” - width of the second groove (Fig. 2). It should be noted that for different dimensions different schemes of machining were done (Figs. 3-5). The dimension “A” (width of the rabbet) was formed as the result of two processes of side milling (Fig. 3). The dimension “B” (width of the first groove) was the result of grooving and additional side milling process (Fig. 4). The dimension “C” was the result of simple grooving process (Fig. 5).

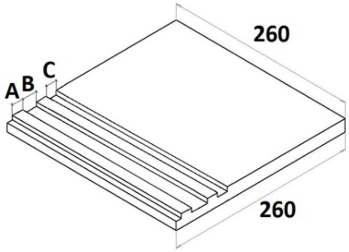

Fig. 2: General view of the workpiece formed in the study.

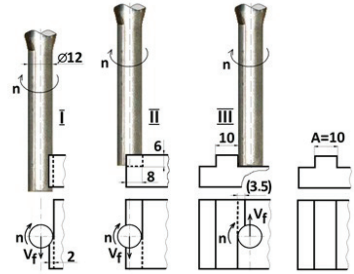

Fig. 3: Scheme of machining (I – initial planing, II – left side milling, III – right side milling) involved in the formation of the dimension "A".

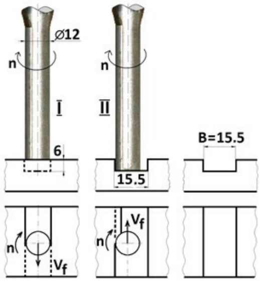

Fig. 4: Scheme of machining (I – grooving, II – side milling) involved in the formation of the dimension "B".

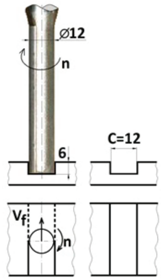

Fig. 5: Scheme of machining involved in the formation of the dimension "C".

All the considered dimensions were measured to determine numerical values of cutting errors. In this way the effect of tool wear on the cutting errors was tested. Five levels of the tool wear (VBmax = 0/0,1/0, 2/0, 3/0, 4 mm) were taken into the account. For each level a series of ten workpieces were observed. So in each case (for each of the twelve cutting conditions variants) there were five workpieces' subgroups (m=5). The size of each subgroup was equal ten (n=10). The widths of the rabbet (the dimension "A") and the grooves (the dimensions "B" and "C") were measured by means of standard outside or inside micrometers (the accuracy of the micrometers was 0.01 mm).

The possible effect of some basic factors - feed per tooth, worked material, clamping system and tool wear - on the value of cutting error was tested by the standard analysis of variance. The statistical significance of the four above factors was formal tested by the multi-factor ANOVA. Moreover, the same basis was used to estimate the relative significance of these factors (in terms of percentage contribution). It should be recalled that the relative significance rate of any factor can be estimated according to following equation:

$$Q_X = (100\ SS_X)/SS_T \qquad (1)$$

where: Q_X – significance rate (percentage contribution) of factor X (%),

SS_X – sum of squares deviations due to factor X,
SS_T – total sum of squares deviations.

In the next phase of the study some basic elements of Statistical Process Control (SPC) theoretical background were used. First of all, the long-term tolerances of considered dimensions were evaluated. The long-term tolerances took into account total (real, long-term) variation of cutting errors. In this case a concept of process performance was used. Process performance is a "statistical measure of the outcome of a characteristic from a process which may not have been demonstrated to be in a state of statistical control" (ISO 21747 2006). The value of the process performance index can be evaluated according to the following formula (ISO 21747 2006):

$$P_P = T/I = (U - L)/(X_{99.835\ \%} - X_{0.135\ \%}) \tag{2}$$

where: P_P – process performance index,
T – specified tolerance,
I – reference interval,
U – upper specification limit,
L – lower specification limit,
$X_{99.835\ \%}$ – $_{99.865\ \%}$ distribution quintile,
$X_{0.135\ \%}$ – $_{0.135\ \%}$ distribution quintile.

It is usually assumed that the satisfactory value of the process performance index equals 1.33 (it is a commonly recommended minimum level of process performance/capability for existing process and for two-sided specifications). Consequently the evaluation of the long-term (real) tolerance of dimension (LT) was based on the following formula:

$$LT = 1.33\ (X_{99.835\ \%} - X_{0.135\ \%}) \tag{3}$$

The formula presented above took into account really observed, total (both within and between subgroups) variation of cutting error. Values of adequate distribution quintiles were evaluated, according to standard statistical methods, as parameters of the distributions fitted to the experimental data. In this way the long-term tolerances (LT_A, LT_B and LT_C (m) for each of the three considered dimensions ("A", "B" and "C") and for each of the twelve cutting condition's variants (Tab. 2) were evaluated. To illustrate the contrast between the long- and short-term tolerances it was necessary to evaluate the latter. The idea of short-term tolerance is that only short-term, i.e. observed only within subgroups, variation of cutting error is taken into account. The between subgroup variation is totally ignored. Therefore, the short-term is only potential (not necessarily real) tolerance. Generally, a short-term tolerance may be regarded as a real tolerance only if process is perfectly centred and stable (in a state of statistical control). It is worth noting that for a stable process between subgroups variation is insignificant because it is the process "subject only to random cause variation" (ISO 21747 2006).

For the short-term tolerance evaluation the concept of process capability was used. In this case the process capability index can be evaluated on the basis of the following formula (ISO 21747 2006):

$$C_P = (U - L)/(6\ S_W) \tag{4}$$

where: C_P – process capability index,
S_W – standard deviation which represents only within subgroup variation.

The above standard deviation can be evaluated in following way (ISO 21747 2006):

$$S_W = (\Sigma S_i)/(m\ c_4) \tag{5}$$

where: S_i – the observed sample standard deviation of the i-th subgroup (i = 1, 2, …, m),
m – total number of observed subgroups of the same size,
c_4 – constant factor based on subgroups size (according to ISO 8258 1991).

It was assumed that the satisfactory value of the process capability index is equal to 1.33. Consequently, the evaluation of the short-term tolerance was done according to the following formula:

$$ST = (8\ \Sigma S_i)/(m\ c_4) \tag{6}$$

where: ST – short-term tolerance of dimension,
S_i – the observed sample standard deviation of the i-th subgroup (i = 1, 2, 3, 4, 5),
m – 5 (number of observed subgroups),
c_4 – 0.973 (according to ISO 8258 1991 for subgroup size equals ten).

This led to the evaluation of the short-term (potential) tolerances for each of the three considered dimensions and for each of the twelve variants of cutting conditions (Tab. 2).

Moreover, the multi-factor ANOVA was used again to formal test the potential effect of cutting conditions - feed per tooth, worked material and clamping system - on short-term tolerance.

RESULTS

During the first phase of the experimental data analysis the cutting errors (e_A, e_B and e_C) observed for the three dimensions ("A", "B" and "C") and for each cutting conditions variant (Tab. 2) were evaluated.

The ANOVA results for values of cutting errors observed for considered dimensions are shown in Tab. 3-5. The p-value indicates the statistical significance level: The lower the p-value; the higher level of statistical significance of a given factor (the p-value of 0.05 was treated as a "border-line acceptable" error level). The significance rates of the factors (Q) in terms of their percentage contribution were estimated according to the equation (1).

Figs. 6-8 show the typical examples of short-term (within subgroup) and long-term (total) variation of the cutting errors depending on tool wear. The positive value of cutting error means, according to adopted convention, that the real dimension of the workpiece turned out to be greater than preferred dimension.

In each case there was a progressive change in the mean value of the cutting error due to progression of tool wear. It should be emphasized that the systematic drift results from the systematic and not random causes (ISO 21747 2006). The undoubted presence of special, not random, cause means that analyzed process is unstable (out of statistical control).

Tab. 3: ANOVA results for values of the cutting error observed for the dimension "A" (all factors turned out to be statistically significant).

Source of variation	Sum of squares (SS)	Degree of freedom (DOF)	F ratio (F)	p-value (p)	Significance rate (Q)
VBmax	21.54170	4	10096.78	< 0.05	97.7 %
Material	0.06271	1	117.57	< 0.05	0.3 %
Clamping	0.01879	1	35.23	< 0.05	0.1 %
Feed per tooth	0.10367	2	97.19	< 0.05	0.5 %
Error	0.31523	592			1.5 %
Total	22.0421				100.0 %

Tab. 4: ANOVA results for values of the cutting error observed for the dimension "B" (all factors turned out to be statistically significant).

Source of variation	Sum of squares (SS)	Degree of freedom (DOF)	F ratio (F)	p-value (p)	Significance rate (Q)
VBmax	10.86579	4	4977.79	< 0.05	96.0 %
Material	0.03215	1	58.91	< 0.05	0.3 %
Clamping	0.03878	1	71.07	< 0.05	0.3 %
Feed per tooth	0.06219	2	56.98	< 0.05	0.6 %
Error	0.32252	592			2.8 %
Total	11.32143				100.0 %

Tab. 5: ANOVA results for values of the cutting error observed for the dimension "C" (all factors turned out to be statistically significant).

Source of variation	Sum of squares (SS)	Degree of freedom (DOF)	F ratio (F)	p-value (p)	Significance rate (Q)
VBmax	5.678506	4	5125.84	< 0.05	96.9 %
Material	0.012918	1	46.64	< 0.05	0.2 %
Clamping	0.002513	1	9.07	< 0.05	0.05%
Feed per tooth	0.002446	2	4.42	< 0.05	0.05 %
Error	0.163680	592			2.8 %
Total	5.860063				100.0 %

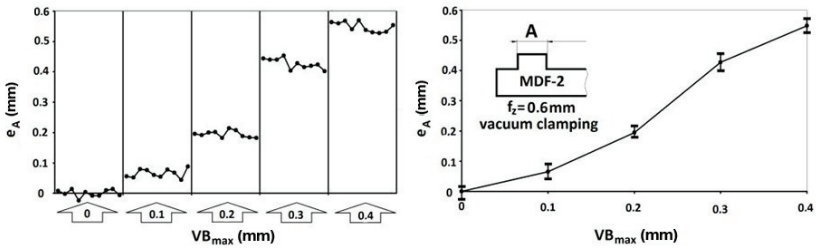

Fig. 6: The example of cutting error variation depending on tool wear - for the dimension "A".

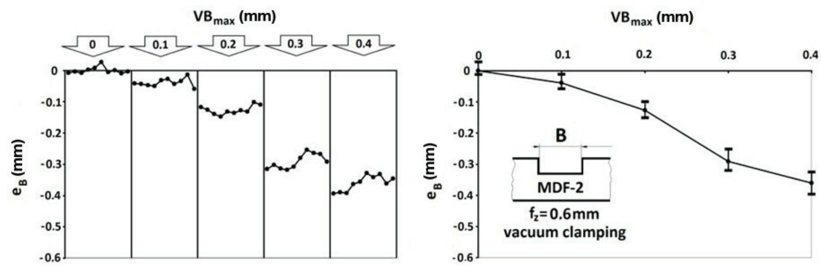

Fig. 7: The example of cutting error variation depending on tool wear - for the dimension "B".

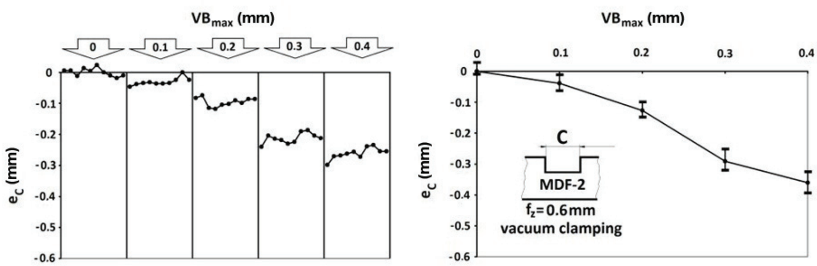

Fig. 8: The example of cutting error variation depending on tool wear - for the dimension "C".

Regardless of this fact the process performance index can be analyzed (ISO 21747 2006).

When it resulted that cutting errors had a systematic drift due to tool wear the following question was asked: what was the relationship between the real (really observed) drift and drift estimated only on the basis of the change in cutting diameter caused by the tool wear. It should be noted that the decrease in cutting diameter can be roughly estimated, due to observed value of flank wear (VBmax), according to following equation:

$$\Delta D = 2\ VB_{max}\ tg(\alpha) \qquad (7)$$

where: ΔD – change (decrease) in cutting diameter,
α – tool clearance angle (15°),
VB_{max} – tool wear indicator.

Figs. 9-11 illustrate the difference between the real drifts and the drifts which were estimated only due to change in cutting diameter caused by tool wear.

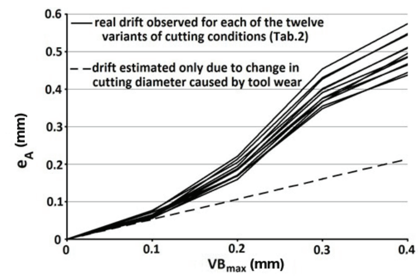

Fig. 9: Real (observed during the experiments for the twelve variants of cutting conditions) and estimated according to equation (7), progressive changes in the mean value of cutting error - for the dimension "A".

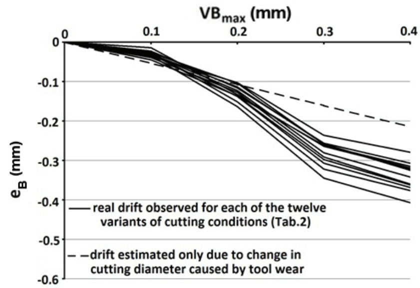

Fig. 10: Real (observed during the experiments for the twelve variants of cutting conditions) and estimated according to equation (7), progressive changes in the mean value of cutting error - for the dimension "B".

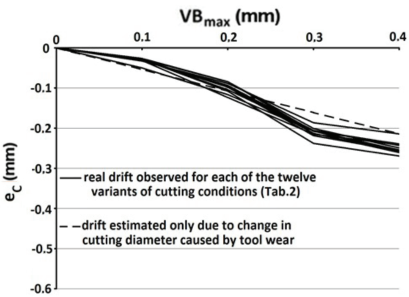

Fig. 11: Real (observed during the experiments for the twelve variants of cutting conditions) and estimated according to equation (7), progressive changes in the mean value of cutting error - for the dimension "C".

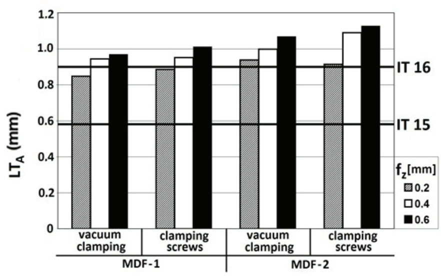

Fig. 12: Long-term tolerance of the dimension "A" (LT_A) observed for different cutting conditions: feed per tooth (f_z), machined material (MDF-1/ MDF-2) and way of clamping (vacuum/ screws).

During the next phase of the experimental data analysis the standardized tolerances for each dimension ("A", "B" and "C") were identified according to ISO 286 2010. Next the long-term (real) tolerances of considered dimensions were evaluated according to equation (3), separately for each cutting conditions variant listed in Tab. 2. The results of these evaluations are shown in Figs. 12-14. For the sake of comparison, the charts show also the adequate standardised tolerances.

Moreover the short-term (potential) tolerances of considered dimensions were evaluated according to equation (6). The evaluation was done for each cutting conditions variant listed in Tab. 2. These tolerances are shown in Figs. 15-17. It is worth recalling that the short-term tolerance would have been real tolerance if the process had been perfectly centered and stable.

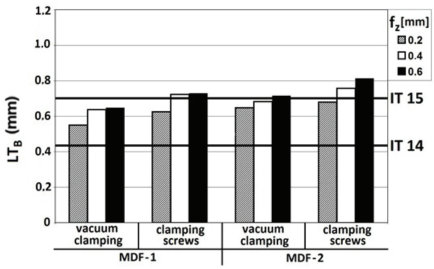

Fig. 13: Long-term tolerance of the dimension "B" (LT_B) observed for different cutting conditions: feed per tooth (f_z), machined material (MDF-1/ MDF-2) and way of clamping (vacuum/ screws).

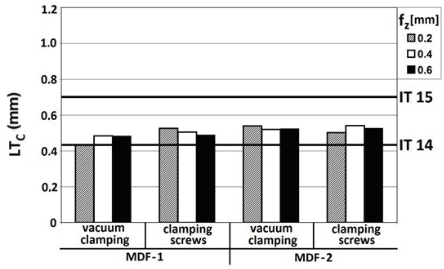

Fig. 14: Long-term tolerance of the dimension "C" (LT_C) observed for different cutting conditions: feed per tooth (f_z), machined material (MDF-1/ MDF-2) and way of clamping (vacuum/ screws).

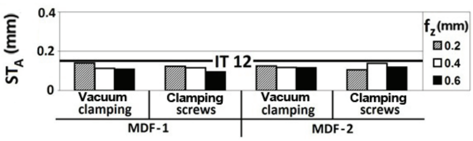

Fig. 15: Short-term tolerance of the dimension "A" (ST_A) observed for different cutting conditions: feed per tooth (f_z), machined material (MDF-1/MDF-2) and way of clamping (vacuum/ screws).

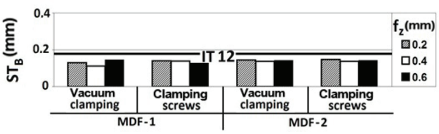

Fig. 16: Short-term tolerance of the dimension "B" (ST_B) observed for different cutting conditions: feed per tooth (f_z), machined material (MDF-1/ MDF-2) and way of clamping (vacuum/ screws).

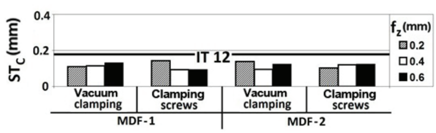

Fig. 17: Short-term tolerance of the dimension "C" (ST_C) observed for different cutting conditions: feed per tooth (f_z), machined material (MDF-1/ MDF-2) and way of clamping (vacuum/ screws).

DISCUSSION

The percent numbers (Q) from Tab. 3-5 show that the only really important factor (i.e. factor which really determined cutting errors observed for particular dimensions) was tool wear (VBmax). In each case the percentage contribution of this factor was not less than 96 %. All the other considered factors - material, clamping system, feed - seemed to be admittedly significant from the statistical point of view but their physical significance turned out to be only symbolic. Their percentage contributions did not exceed 0.6 %.

Generally the cutting errors had a systematic drift due to tool wear but it turned out that the scheme of machining (Figs. 3-5) had a very significant impact on the relationship between the real (really observed) drift and drift estimated only on the basis of the change in cutting diameter caused by the tool wear. The real drifts and estimated drift of the cutting errors were comparable

(Fig. 11) only for simple grooving (Fig. 5). The most significant differences (Fig. 9) were observed for the dimension "A" which was formed by means of the double side milling process (Fig. 3). About half smaller, but also significant, differences (Fig. 10) were observed for the dimension "B" which was formed by means of grooving and additional side milling process (Fig. 4). It generally means that cutting diameter monitoring can be useless in cutting error prediction or compensation. It is true regardless of whether change in this diameter would be roughly estimated or accurately measured. Ohuchi and Murase (2006) admittedly showed that precise measuring of decrease in cutting diameter can be effective for adaptive control grooving system but generally it is the workpiece, rather than the tool, which should be measured for adequate corresponding to progression of tool wear. It is worth adding here, that the authors developed the special machine (computer) vision algorithm, which makes it possible to automatically measure the dimensions "A", "B" and "C". It is extremely important since this algorithm might be used in adaptive control system.

Moreover, also in contrast to earlier studies (Ohuchi and Murase 2001, 2006), the problem of MDF milling process's dimensional accuracy was analyzed according to ISO standards (ISO 21747 2006 and ISO 286 2010). It turned out that in most cases the long-term (real) tolerances estimated for the dimension "A" exceeded the limit of IT16 (Fig. 12). Better results were observed for the dimension "C" – the long-term (real) tolerances did not exceed IT15 limit (Fig. 14). Interestingly it turned out that the short-term (potential) tolerances estimated for any dimension did not exceed the limit of IT12 (Figs. 15, 16 and 17). In this way, it was found that progression of tool wear can reduce a machining accuracy from IT12 to IT17.

CONCLUSIONS

The significant tool wear (VBmax = 0.4 mm) can reduce a machining accuracy from IT12 (tolerance grade which represents extremely high level of accuracy in furniture manufacturing) to IT17 (last but one, in terms of accuracy, tolerance grade defined in ISO 286 2010). A progression of tool wear causes evidently systematic increase in cutting error, which means that machining process becomes unstable.

To ensure an adequate reaction to the progression of tool wear during any MDF milling process it is a workpiece rather than a tool which should be measured (monitoring of decrease in cutting diameter can be useless when side milling process is involved).

REFERENCES

1. Aguilera, A., 2010: Cutting energy and surface roughness in medium density fiberboard rip sawing. Eur. J. Wood Prod. 69(1): 11-18.
2. Aguilera, A., Meausoone, P.J., Martin, P., 2000: Wood material influence in routing operations: The MDF case. Holz als Roh– und Werkstoff 58(4): 278-283.
3. Davim, J.P., Clemente, V.C., Silva, S., 2009: Surface rough aspects in milling MDF (medium density fibreboard). J. Adv. Manuf. Technol. 40(1-2): 49-55.
4. Gaitonde, V.N., Karnik, S.R., Davim, J.P., 2008: Taguchi multiple-performance characteristics optimization in drilling of medium density fibreboard (MDF) to minimize delamination using utility concept. Journal of Materials Processing Technology 196(1-3): 73-78.

5. ISO 21747, 2006: Statistical methods - Process performance and capability statistics for measured quality characteristics.
6. ISO 286-1, 2010: Geometrical product specifications (GPS) - ISO code system for tolerances on linear sizes. Part 1: Basis of tolerances, deviations and fits.
7. ISO 286-2, 2010: Geometrical product specifications (GPS) - ISO code system for tolerances on linear sizes. Part 2: Tables of standard tolerance classes and limit deviations for holes and shafts.
8. ISO 8258, 1991: Shewhart control charts.
9. Laszewicz, K., Górski, J., 2010: Dimensional accuracy of wood based materials machining in furniture production – general problems and initial study. In: Wood machining and processing – product and tooling quality. (ed. J. Górski, M. Zbieć). Pp 25-43, WULS – SGGW Press, Warsaw.
10. Maness, T.C., Kozak, R.A., Staudhammer, C., 2003: Applying real-time statistical process control to manufacturing processes exhibiting between and within part size variability in the wood products industry. Journal of Quality Engineering 16(1): 113-125.
11. Maness, T.C., Kozak, R.A., Staudhammer, C., 2004: Reliability testing of statistical process control procedures with multiple source of variation. Wood and Fiber Science 36(3): 443-458.
12. Maness, T.C., Staudhammer, C., Kozak, R.A., 2002: Statistical considerations for real-time size control systems in wood products manufacturing. Wood and Fiber Science 34(3): 476-484.
13. Staudhammer, C., Lemay, V.M., Maness, T.C., Kozak, R.A., 2005: Mixed-model development of real-time statistical process control data in wood products manufacturing. Forest Biometry, Modelling and Information Science 1: 19-35.
14. Staudhammer, C., Kozak, R.A., Maness T.C., 2006: SPC methods for detecting simple sawing defects using real-time laser range sensor data. Wood and Fiber Science 38(4): 696-716.
15. Staudhammer, C., Maness, T.C., Kozak, R.A., 2007: Profile charts for monitoring lumber manufacturing using laser range sensor data. Journal of Quality Technology 39(3): 224-240.
16. Ohuchi, T., Murase, Y., 2001: On the machining accuracies for grooving and side milling with a CNC router. Pp 447–455. Proceedings of the 15th IWMS, L.A.
17. Ohuchi, T., Murase, Y., 2005: Milling of wood and wood-based materials with a computerized numerically controlled router IV: Development of automatic measurement system for cutting edge profile of throw-away type straight bit. J. Wood. Sci. 51(3): 278-281.
18. Ohuchi, T., Murase, Y., 2006: Milling of wood and wood-based materials with a computerized numerically controlled router V: Development of adaptive control grooving system corresponding to progression of tool wear. J. Wood. Sci. 52(5): 395-400.
19. Ohuchi, T., Lin, H.C., Fujiomoto, N., Murase, Y., 2008: Development of automatic system for monitoring and removing of burr in side milling process of wood and wood-based materials. J. Fac. Agr. Kyushu Univ. 53(1): 101-105 (in Japanese).
20. Young, T.M., Bond, B.H., Wiedenbeck, J., 2007: Implementation of a real-time statistical process control system in hardwood sawmills. Forest Products Journal 57(9): 54-62.
21. Young, T.M., Winistorfer, P.M., 1999: Statistical process control and the forest products industry. Forest Products Journal 49(3): 10-17.
22. Young, T.M., Winistorfer, P.M., Siqun, W., 1999: Multivariate control charts of MDF and OSB vertical density profile attributes. Forest Products Journal 49(5): 79-86.

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