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DETERMINATION OF MAXIMUM TORQUE DURING CARPENTRY WASTE COMMINUTION

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ABSTRACT

In order to elaborate design guidelines for developing efficient and possibly most energy saving mills for comminuting carpentry, OSB and MDF waste, there have been performed some tests aimed at torque demand on the working unit of the machinery participating in that process. The tests were carried out on a cylindrical wood chipper. There were indicated the maximum, minimum and average values of the torque, indispensable for the comminution of boards with defined geometric sizes (5 - 50 mm wide) and thickness (3 - 28 mm). The value of torque required in the comminution of carpentry waste increases with growing cross section, and the torque vs. cross section relation is approximately linear. The presented values may constitute not only a set of input data indispensable for modeling the power which is necessary for the comminution process, but they can also enable the validation of the existing cutting models with a single cylinder cutter.

KEYWORDS: Cutting forces, wood chipper, MDF board, OSB board, chipboard, carpentry waste, comminuting mill.

INTRODUCTION

Consumerism intensifies worldwide, which leads to increased demand for new household furnishings and is reflected in increased sales volumes in the furniture industry. According to the 2021 year estimates, this trend will continue (Pavlov 2019). In consequence, the volume of carpentry waste increases. Main waste in today's carpentry workshops are furniture boards consisting, first of all, of chips and wood dusts in PCV laminates (Narlıoğlu et al. 2018). Most used furniture materials are as follows: furniture grade plywood, chip boards, fiber boards including oriented strand boards (OSB), low density fiberboards (LDF), medium density fiberboards (MDF) or high density fiber boards (HDF) (Wasielewski 2019). Such materials are made mainly of wood fibers and contain up to 10% of synthetic additives, like glues, laminates, varnishes and surface modifiers (Stubdrup et al. 2016, Wasielewski 2019). Because of the materials used in the manufacturing process, there will occur problematic waste which needs appropriate utilization.

Chemical energy contained in the waste may be utilized for energy generation purposes, viz. electricity or thermal energy in various technological variants of thermochemical convection, e.g. incineration, pyrolysis, gasification, plasma processes and their combinations (Król 2008, Wasielewski and Bałazińska 2017). Moreover, such a type of waste is characterized with high contents of wood - a biodegradable fraction - which may mean extra profits in relation to the qualification and clearing of generated electricity as such which, to a certain extent, comes from renewable sources (Wasielewski and Bałazińska 2017). For a possible environmental hazard, the energy recovered from waste is subject to particular legislative determinants (Wasielewski and Bałazińska 2017). They regard mainly the processing requirements related to the management of emission measurements and compliance with the emission standards (Wasielewski and Bałazińska 2017). Industrial waste is incinerated in purpose-built installations which limit the volume of deleterious substances released into the air, of which gravest concern are dusts, fly ashes, acid gases as well as aerosols of heavy metals (Król 2008). Both appropriate selection of incineration parameters and the application of correct technology of waste gas cleaning may guarantee a low emission heat source for industrial establishments (Karol 2008). Factory furnaces, used in such processes, are adapted to the incineration of comminuted fiber board and wood-based waste, and are characterized with high temperatures in the burning chamber (at least 850°C) as well as an after-burning chamber with additional burners. Such modern facilities are adapted to the incineration of comminuted waste. It is easier to transport commuted waste (Reczulski 2015), to store it and eventually to support incineration technologies. In the references available there are some results of the investigations into the materials used in furniture production. Those results concern mechanical and physical properties of furniture boards with diversified analyses and structures (Pritchard et al. 2001, Akyüz et al. 2010, de Barros Filho et al. 2011, Ayrilmis et al. 2007, Ganey et al. 2007, Rydzkowski and Michalska-Pożoga 2016, Akyildiz et al. 2018). Then, there are also published models which allow estimating forces in the process of cutting or machining wood or wood-based materials on such machines, like a circular saw (Porankiewicz et al. 2011, Orłowski et al. 2013, Kopecký et al. 2014), a band saw (Orłowski and Ochrymiuk 2017, Chuchała and Orłowski 2018), a chain saw (Kuvik et al. 2017), a large size crusher (Yu et al. 2012), a milling machine (Džinčić et al. 2012, Guo et al. 2015, Mandić et al. 2015, Krauss et al. 2016, Durković et al. 2018, Kopecký et al. 2019), as well as in the case of cutting along the direction pre-determined in relation to the specimen (Porankiewicz and Goli 2014). Nevertheless, there is no information available for designers of mills comminuting furniture waste, and precisely, about the forces to be carried by their working units, and thus, also about the power demand for the drives. Adequate selection of the driving unit without great power reserve is reflected in quantifiable ecological and economic benefits related to saving the energy in the process under execution (Waluś et al. 2018, Warguła et al. 2019). This article presents average torque values for comminuting carpenter waste - laminated particle board (PB-L) and non-laminated PB boards, OSB and MDF with a single cylinder wood chipper. The effect of the number of cutting blades upon the torque was also proved. The final results are to be used in future for developing and validating a model and for determining the maximum power indispensable for the execution of furniture waste comminution with a single cylinder wood chipper.

MATERIALS AND METHODS

Waste wood-based furniture boards were selected for test specimens. They were segregated and ranked in line with Tab. 1, taking into consideration the type of material, its thickness and width. From among waste products, there were selected particle boards made of wood chips bonded with each other with synthetic glues and pressed at a high temperature. Those boards were also divided according to the presence or absence of an external laminate. Another group of particle boards were OSB made of relatively big, oblong chips, juxtaposed with longitudinal axes arranged in one direction of the sheet. The last group of boards subject to investigation was MDF. They are dry shaped and their density lies in an interval from 500 kg·m^{-3} to 900 kg·m^{-3}. The samples under tests were subject to conditioning, and their humidity did not exceed 4%.

Tab. 1: Materials subjected to comminution.

<table>
<tr><th>Type of board</th><th colspan="5">Thickness (mm)</th><th colspan="9">Width (mm)</th></tr>
<tr><td>Particle board with laminate (PB-L)</td><td>10</td><td colspan="2">18</td><td colspan="2">28</td><td rowspan="4">10</td><td rowspan="4">15</td><td rowspan="4">20</td><td rowspan="4">25</td><td rowspan="4">30</td><td rowspan="4">35</td><td rowspan="4">40</td><td rowspan="4">45</td><td rowspan="4">50</td></tr>
<tr><td>Particle board without laminate (PB)</td><td>12</td><td colspan="2">18</td><td colspan="2">25</td></tr>
<tr><td>Oriented strand board (OSB),</td><td>12</td><td colspan="2">16</td><td>18</td><td>26</td></tr>
<tr><td>Medium density fiberboard (MDF)</td><td>3</td><td>8</td><td>10</td><td>14</td><td>20</td></tr>
</table>

The experiments were carried out on a test stand for investigating into wood comminution processes (Warguła et al. 2018). That stand was based upon a Macalister MQS2800 electric comminuting mill, designed for wood comminution (Fig. 1).

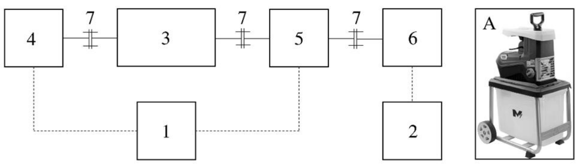

Fig. 1: Scheme of the test stand: 1 – recording computer, 2 – wood chipper controller, 3 – working unit, 4 – RPM sensor, 5 – torque measurement device, 6 – drive motor, 7 – clutch; detail A shows the cylinder wood chipper before fitting the measurement devices.

In order to enable investigations into kinetic and dynamic properties of the comminution process, the wood chipper was supplemented with measurement devices. The torque characteristic was measured and recorded by means of a versatile torque measurement device. The rotational speed was measured with a Megatron MOB 2500/5/BZ/N encoder. Data acquisition was possible due to dedicated proprietary computer software. In each measurement test, 10 specimens, with pre-determined properties, geometry and material, were examined as presented in Tab. 1.

RESULTS AND DISCUSSION

The results of the tests performed include time functions for the torque and rotational speed of the working unit. Selected curves for the recorded results are shown in Fig. 2. From the time interval in which the comminution process was performed (interval d) determined was a series of maximum torque values. The arithmetic mean of those values was taken as the estimator for the value to be found.

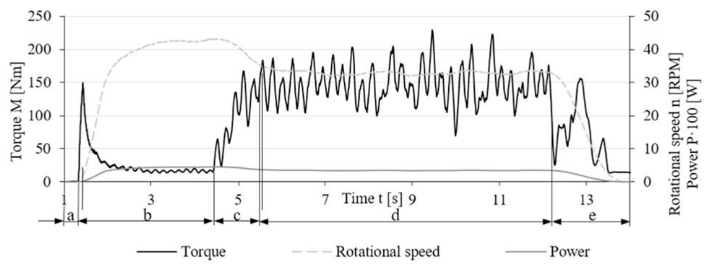

Fig. 2: Torque vs. time and RPM vs. time curves for the comminution of a laminated particle board 18 mm thick and 50 mm wide; indicated are some selected process intervals: a – machine switched off, b – mill start-up, c – comminution started, d – comminution in course, e – comminution ended.

The selected torque vs. time curve during the comminution process indicating both the maximum values occurring in the cutting process and the determined arithmetic mean of the maximum torque were shown in Fig. 3.

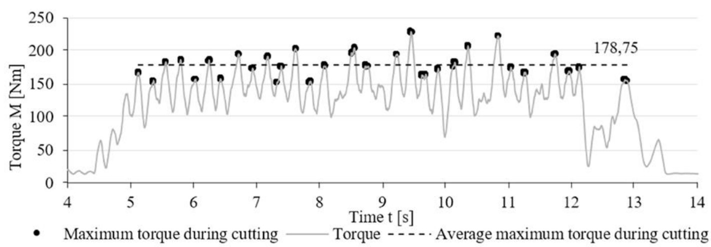

Fig. 3: Torque vs. time curve for the comminution of a laminated particle board 18 mm thick and 50 mm wide; indicated are the maximum values for the cutting process, with the determination of the arithmetic value.

Basing upon the collected curves there were determined the average maximum torque values for the comminution of furniture boards, and indicated were the maximum and minimum values (Tabs. 2-4).

Tab. 2: Maximum torque value for the comminution of a PB and a laminated PB-L, where: A – width, B – arithmetic mean, C – maximum value, D – minimum value.

Particle Board						
	with laminate			without laminate		
A	B	C	D	B	C	D
mm	Nm					
	Thickness 10 mm			Thickness 12 mm		
10	23.91	31.77	20.02	14.38	26.98	10.02
15	33.94	44.49	30.03	26.53	38.57	20.31
20	34.93	41.13	30.02	29.59	37.93	25.19
25	41.68	54.24	35.09	37.08	49.18	30.23
30	52.73	66.78	49.7	42.48	54.3	35.04

35	63.84	75.49	62.53	58.01	75.24	45
40	66.38	84.64	61.21	59.01	77.46	50.08
45	68.94	82.7	60.5	74.14	92.73	60.15
50	74.08	86.41	68.26	73.76	87.76	66
	Thickness 18 mm					
10	29.78	37.8	25.02	31.01	41.07	25.01
15	50.2	64.92	45	59.83	77.96	50
20	69.17	86.62	60.04	66.04	83.62	55.1
25	80.68	107.93	70	75.64	107.54	65
30	100.52	140.95	90	83.71	121.305	65.44
35	105.06	113.93	95.01	99.69	135	77.61
40	123.5	160.02	110.01	110.02	132	91.23
45	131.08	197.93	100	125.67	178.73	100.19
50	178.75	229.11	154.8	134.36	159.56	110.56
	Thickness 28 mm			Thickness 25 mm		
10	27.77	93.65	20	27.47	51.28	19.87
15	62.34	105.1	45.03	61.9	103.09	45.47
20	69.23	164.97	55	68.71	120.97	55.01
25	77.95	166.87	69.54	78.86	133.67	71.33
30	88.84	134.95	75.01	92.49	156.87	83.21
35	115.29	150.56	95.21	101.86	147.56	80.04
40	112.31	196.66	100.02	106.29	193.66	90.03
45	135	222.32	112.6	128.52	225.31	95.32
50	152.32	243	121.52	149.55	240.4	110.81

Tab. 3: Maximum torque values for OSB comminution, where: A-width, B – arithmetic mean, C – maximum value, D – minimum value.

A	B	C	D	B	C	D
mm	Nm					
	Thickness 12 mm			Thickness 16 mm		
10	19.62	26.32	17.01	21.38	25.43	16.78
15	20.66	25.31	18.12	26.01	33.12	20.32
20	31.93	40.06	26.19	37.98	53.49	32.02
25	34.54	44.27	30.13	56.52	73.25	50.21
30	40.92	48.72	35.29	64.01	91.07	55.37
35	52.18	82.15	45.02	79.21	112.11	71.2
40	61.96	79.59	53.23	90.17	103.7	80.33
45	73.13	95.18	65.56	97.24	112.33	85.06
50	76.52	104.24	70.12	105.83	132.32	91.71
	Thickness 18 mm			Thickness 26 mm		
10	37.32	50.22	27.52	43.83	65.77	35.02
15	61.28	80.29	48.01	81.39	95.55	69.34
20	81.48	126.99	69.21	92.86	84.47	111.42
25	95.81	131.04	80.12	129.43	177.13	110.04

30	119.39	156.07	95.06	140.21	215.86	120.05
35	129.09	157.99	115.02	192.02	277.86	148.93
40	151.43	198.06	129.87	227.79	301.31	198.56
45	169.49	201.98	135.98	270.71	344.817	231.86
50	198.21	227.48	153.67	276.95	418.51	250.01

Tab. 4: Maximum torque values for MDF comminution, where: A – width, B – arithmetic mean, C – maximum value, D – minimum value.

A	B	C	D	B	C	D
mm	Nm					
	Thickness 3 mm			Thickness 8 mm		
10	11.34	15.78	10.21	23.48	28.23	19.02
15	13.2	19.7	12.33	30.42	27.3	25.39
20	16.28	21.06	14.12	39.46	53.26	30.92
25	19.42	21.28	18.36	44.56	54.18	33.45
30	25.09	27.99	21.02	48.33	56.98	36.21
35	26.39	31.57	22.15	54.43	63.85	35.95
40	28.43	32.14	25.44	60.62	78.65	45.35
45	30.15	35.45	25.56	65.56	71.67	51.99
50	33.87	35.52	27.28	74.62	79.65	50.3
	Thickness 10 mm			Thickness 14 mm		
10	20.28	24.29	18.03	14.55	20.68	12.45
15	28.23	34.56	26.97	23.56	28.34	20.11
20	35.58	43.24	32.09	33.65	40.56	31.92
25	43.19	49.81	39.12	38.33	48.87	55.07
30	45.53	51.72	42.01	41.53	57.12	38.54
35	55.21	65.87	50.07	66.95	79.23	60.23
40	57.16	62.05	55.46	71.95	87.69	63.09
45	70.52	82.64	61.21	78.17	87.34	71.22
50	75.59	92.68	66.94	84.86	99.83	77.39
	Thickness 20 mm					
10	51.53	65.86	45.29			
15	81.3	93.19	75.05			
20	89.87	105.85	81.88			
25	103.59	112.78	92.64			
30	115.8	136.56	91.34			
35	120.47	131	95.56			
40	151	175.46	129.76			
45	193.89	236.94	154.35			
50	230.45	311.23	211.23			

Actual torque dynamic characteristics of the working unit of the Macalister MQS2800 wood chipper exhibit certain variability, which is attributable to a sudden and step-like cyclic nature of the comminution process. The determined values are also influenced by interference caused, for example, by non-ideal balancing of the rotary parts of the working unit of the wood chipper. Nevertheless, the recorded data constitute a valuable source of information in view of designing and operating such a type of machinery. It is also possible to observe typical nature of the occurring changes and to determine their scale.

The unloaded working unit generates a torque of approx. 10 Nm which results from the internal resistances of the mill, e.g. friction in the bearings. The comminution process generates a variable characteristic, which results from cutting orthotropic plant-based materials with anisotropic structures. Due to the comminution of the specimens said, it is possible to determine the variability characteristic of torque according to the geometry of the material subject to grinding (Fig. 4).

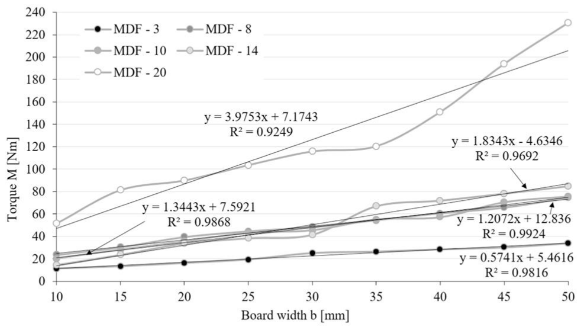

Fig. 4. Torque vs. width (of board under comminution) curves in the comminution process, taking into consideration the material and width, where at the legend of the graphs are indicated characteristics adequate for the line trend of the curves shown.

The collected data indicate that the torque value increases with increasing cross-section of the board under comminution, which is caused by a growing cutting area. The occurring changes may be acknowledged linear with sufficient approximation. It can be noticed that in the case of similar cross-sections, the highest resistance is generated by a MDF, followed by an OSB. The lowest value of the cutting force is required while comminuting a particle board. It is worth stressing that the use of surface laminate increases a board's shear resistance, most probably because of high hardness of that layer. The maximum torque value in the comminution process depends on the number of blades involved (Tab. 5).

Tab. 5: Percentage involvement of the second blade according to the thickness of the board subject to comminution; G –thickness; H – α angle value, J – number of operating blades, P – percentage involvement of the other blade in the cutting process.

G (mm)	3	8	10	12	14	18	20	25	26	28
H (°)	21.28	35.1	39.4	43.34	47.01	53.78	56.94	64.42	65.85	68.68
J (-)	1	1	1	1	2	2	2	2	2	2
P (%)	0	0	0	0	0.94	4.72	6.8	12.5	13.73	16.26

Basing upon the tool geometry and the grinding process performed by means of a single cylinder wood chipper shown in Fig. 5 one may determine the number of the blades involved, according to the thickness of material subject to comminution. For a tool with eight symmetrically arranged blades, in the comminution process involved are two blades if the angle between the cutter's blade and the face of the piece under comminution α is > 45°.

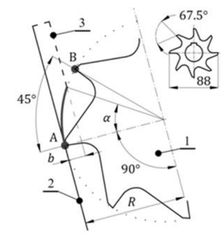

Fig. 5. Geometry of comminution process with a single cylinder wood chipper, where: 1 – grinding cutter, 2 – pressure plate, 3 – material under comminution, L – length of surface under comminution, b – thickness of material under comminution, R – blade radius of the mill, α – theoretical angle required for cutting the material through, A – vertex of the first blade, B – vertex of the second blade.

The percentage involvement of the other blade in the cutting process *P* can be found from Eq. 1:

$$P = \frac{(\alpha - 45°) \cdot 100}{\alpha} \quad (\%) \tag{1}$$

where: α is the angle between the cutter's blade and the face of the piece being comminuted.

Comparing the results obtained from the comminution of pine wood beams, sized 18 × 18 mm (Warguła et al. 2019) and of beams of particle board, having similar sizes, viz. (18 × 20 mm), OSB (18 × 20 mm) and MDF (20 × 20 mm), it can be estimated that the torque value in the comminution of industrial furniture waste is lower and lies in an interval from 30% to 49%. Basing upon the geometry of waste available in a factory or the geometry of the working unit and the feeding chute of the machine, it is possible to estimate the load on the driving unit. It is advantageous to select such a drive whose power does not significantly exceed the value resulting from the torque indispensable for comminuting the waste. This is of particular significance since the power for the driving unit is one of the fundamental factors influencing the energy consumption of the mill. Such a conclusion is corroborated by the test results (Facello et al. 2013, Manzone 2015, Shahid et al. 2019) concerning the comminution of tree trunks and branches with wood chippers which have the drive units with diversified power values (Fig. 6).

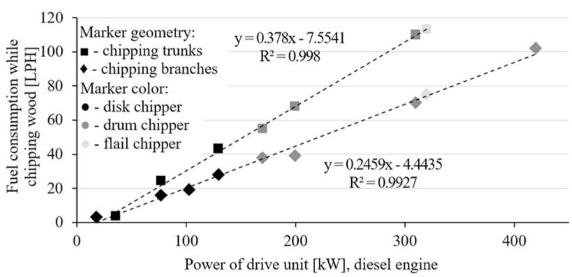

Fig. 6. Fuel consumption of heavy duty, self-ignition engined industrial wood chipper (elaborated basing upon results of investigations (Facello et al. 2013, Manzone 2015, Shahid et al. 2019).

It was proved that among many factors influencing the energy consumption in the comminution process, the power of the drive unit exerts the greatest influence upon energy consumption. A limitation of energy consumption during the operation of such a machinery is supported by adaptive systems (Warguła et al. 2017), alternative supply sources of drives (Szpica and Czaban 2014) as well as by innovative working units (Macok et al. 2018). However, it is adequate selection of the drive power vs. real power demand to guarantee the most efficient utilization of the energy supplied for the comminution process.

Tab. 6: Linear function approximation coefficients for a torque change dependent upon the thickness of materials under comminution and their types.

Material – thickness (mm)	Linear approximation	Coeff. of determination (R^2)
PB laminated – 10	y = 1.3025x + 12.085	0.968
PB laminated – 18	y = 3.2385x - 0.6293	0.9609
PB laminated – 28	y = 2.7989x + 9.482	0.9668
PB not laminated – 12	y = 1.5337x + 0.0969	0.9758
PB not laminated – 18	y = 2.4098x + 15.037	0.9808
PB not laminated – 25	y = 2.6211x + 11.994	0.9617
OSB – 12	y = 1.5424x - 0.5532	0.9769
OSB – 16	y = 2.2619x - 3.5949	0.9886
OSB – 18	y = 3.8046x + 1.8074	0.9941
OSB – 26	y = 6.1096x - 21.601	0.9816

During the tests, absolute increment values were also applied for analyzing the effect of the respective variables exerted upon the experimental results. So as to estimate the scale of the occurring changes there were used torque increments *vs.* specimen thickness ΔM_1, torque increments vs. specimen widths ΔM_2 and torque increments ΔM_3, in line with the relationships (2) - (4):

$$\Delta M_1 = M_{gmax} - M_{gmin} \qquad \text{(N.m)} \tag{2}$$

$$M_2 = M_{bmax} - M_{bmin} \qquad \text{(N.m)} \tag{3}$$

$$\Delta M_3 = M_{rmax}^{MDF} - M_{rmin} \qquad \text{(N.m)} \tag{4}$$

where: M_{gmax} and M_{gmin} stand, respectively, for the highest and the lowest average torque values for the same width and type, but with different thicknesses, M_{bmax} i M_{bmin} are, respectively, the highest and the lowest torque value for a MDF specimen of the same thickness and type but with different widths, M_{rmax}^{MDF} means the average torque value for a MDF specimen with a given thickness and width, and eventually, M_{rmin} stands for average torque values for a specimen with the same width and similar thickness, but of other type of material.

Material from a laminated and non-laminated plywood and OSB, 18 mm thick, was chosen for calculating the last coefficient. In the case of the MDF board, the closest thickness value was chosen, viz. 20 mm. For the nature of the specimens under examination (wastes), it was impossible to select a 18 mm thick MDF. The respective graphs are shown in Figs. 7-9.

An analysis of the presented graphs allows one to conclude that the highest absolute increment of the average torque value, according to the thickness, amounted to 233.12 Nm (Fig. 7) and was recorded for an OSB. Basing thereupon it can be stated that in line with the tests performed, the thickness of the pieces subject to comminution has the crucial effect upon the torque required in this process. The reason for such a great increment is that as then specimen thickness grows; the share of the respective cutting blades in the comminution process will also increase. The more blades contact the material, the higher demand for driving torque. The highest absolute increment of the average torque value according to the specimen width was 200.43 Nm. An analysis of the graph in Fig. 8 permits to ascertain that a constant increase in the torque value depends upon the width, which results from an increased cross section of the material under comminution – the larger the board area, the greater torque demand. The values shown in Fig. 9 are shown with previous reservation pertinent to the specimen thickness. Nevertheless, it can be noticed that the largest change recorded is 96.09 Nm. Of course, the type of material exerts a significant effect upon the maximum recorded values of torque required for grinding the material. However, during the tests performed similar materials were subject to comminution. Most probably that is why for similar specimen thicknesses obtained were average maximum torque values which differ one from another to the least possible extent in relation to the thickness and width.

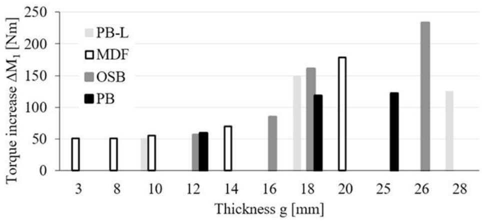

Fig. 7. Torque increment ΔM_1 according to the thickness of specimens.

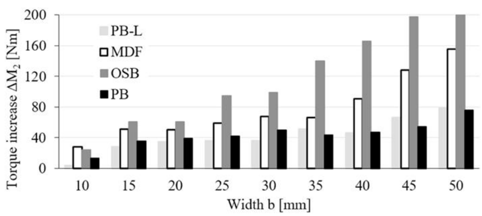

Fig. 8. Torque increment ΔM_2 according to the width of specimens.

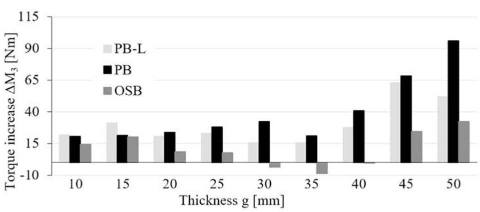

Fig. 9. Torque increment ΔM_3 according to the type of specimens.

CONCLUSIONS

The crucial conclusions concerning the effect of the type and size of industrial furniture board waste exerted upon the torque during the comminution by means of a wood chipper are as follows: (1) In the process of comminution of industrial furniture board waste, the torque value increases approximately linearly with growing cross sectional thickness. The highest recorded absolute change of the average value of the driving torque is around 233 Nm. (2) In the process of comminution of industrial furniture board waste, the torque value increases with growing cross sectional width. The highest recorded absolute change of the average value of the driving torque is around 200 Nm. (3) In the process of comminution of industrial furniture board waste, the torque value changes with the change of the material type. The highest recorded absolute change of the average value of the torque referred to MDF boards is around 96 Nm. (4) The maximum torque for materials with similar thickness is required for comminuting a MDF, followed by an OSB, and the smallest force is required for comminuting a particle board. (5) Laminated particle boards entail a higher torque for the comminution than non-laminated ones do. (6) It can be estimated that for the comminution of furniture wastes - if compared to wood (pine) wastes - the required power of the driving unit is lower by about 30%. (7) An increased number of cutting blades (for a constant thickness of a part subject to comminution) increases the value of the torque required. (8) The choice of the tool geometry according to the thickness of waste being comminuted - in which case only one cutting blade is necessary - may limit the power demand of the drive unit, and thus, decrease the energy consumption in the process. (9) The significance of the tests shown in this paper is derived from the set of the results obtained. Those results can be utilized for works related to the development and validation of mathematical models to describe the power demand in the comminution process. They also constitute a set of input parameters which may be used in designing comminuting machinery operated with a single cylinder cutter.

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