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).

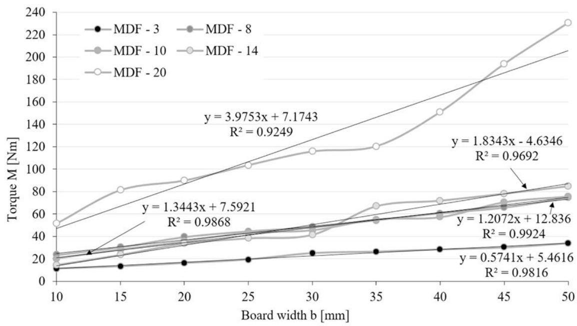

Fig. 4. Torque vs. width (of board under comminution) curves in the comminution process, taking into consideration the material and width, where at the legend of the graphs are indicated characteristics adequate for the line trend of the curves shown.

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°.

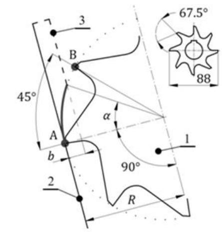

Fig. 5. Geometry of comminution process with a single cylinder wood chipper, where: 1 – grinding cutter, 2 – pressure plate, 3 – material under comminution, L – length of surface under comminution, b – thickness of material under comminution, R – blade radius of the mill, α – theoretical angle required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

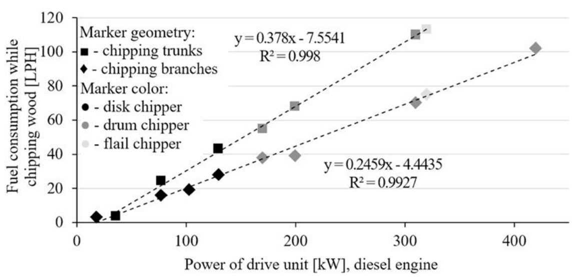

Fig. 6. Fuel consumption of heavy duty, self-ignition engined industrial wood chipper (elaborated basing upon results of investigations (Facello et al. 2013, Manzone 2015, Shahid et al. 2019).

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):

$$\Delta M_1 = M_{gmax} - M_{gmin} \quad \text{(N.m)} \tag{2}$$
$$M_2 = M_{bmax} - M_{bmin} \quad \text{(N.m)} \tag{3}$$
$$\Delta M_3 = M_{rmax}^{MDF} - M_{rmin} \quad \text{(N.m)} \tag{4}$$

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.

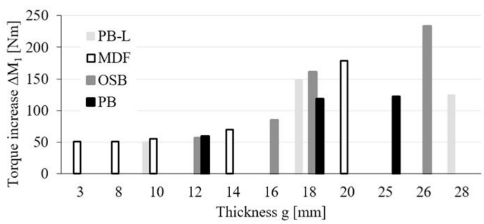

Fig. 7. Torque increment ΔM_1 according to the thickness of specimens.

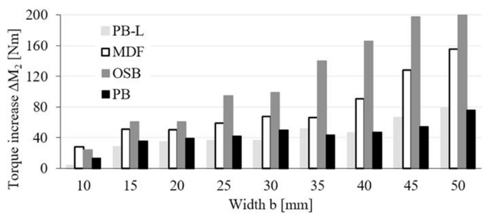

Fig. 8. Torque increment ΔM_2 according to the width of specimens.

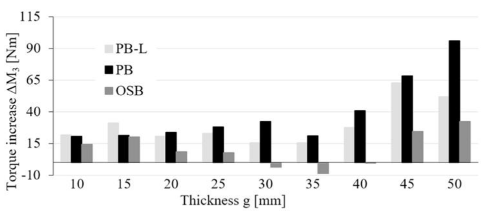

Fig. 9. Torque increment ΔM_3 according to the type of specimens.

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.

REFERENCES

1. Akyildiz, M.H., Dogan, K., Kaymakci, A., 2018: The impact of density and mixture ratio of melamine on some properties of oriented strand board. Maderas. Ciencia y tecnología 20(3): 417-430.
2. Akyüz, K.C., Nemli, G., Baharoğlu, M., Zekoviç, E., 2010: Effects of acidity of the particles and amount of hardener on the physical and mechanical properties of particleboard composite bonded with urea formaldehyde. International Journal of Adhesion and Adhesives 30(3): 166-169.
3. Ayrilmis, N., Candan, Z., White, R., 2007: Physical, mechanical, and fire properties of oriented strandboard with fire retardant treated veneers. Holz als Roh-und Werkstoff 65(6): 449-458.
4. Chuchała, D., Orłowski, K., 2018: Forecasting values of cutting power for the sawing process of impregnated pine wood on band sawing machine. Mechanik 2018(8-9): 766-768.
5. de Barros Filho, R.M., Mendes, L.M., Novack, K.M., Aprelini, L.O., Botaro, V.R., 2011: Hybrid chipboard panels based on sugarcane bagasse, urea formaldehyde and melamine formaldehyde resin. Industrial Crops and Products 33(2): 369-373.
6. Durković, M., Mladenović, G., Tanović, L., Danon, G., 2018: Impact of feed rate, milling depth and tool rake angle in peripheral milling of oak wood on the cutting force. Maderas. Ciencia y tecnología 20(1): 25-34.
7. Džinčić, I., Skakić, D., 2012: Determining the parameters of wood machinability as a function of tangential cutting force during the process of machining wood by routing. Wood Research 57(1): 161-172.
8. Facello, A., Cavallo, E., Magagnotti, N., Paletto, G., Spinelli, R., 2013: The effect of chipper cut length on wood fuel processing performance. Fuel processing technology 116: 228-233.

9. Ganev, S., Gendron, G., Cloutier, A., Beauregard, R. 2007: Mechanical properties of MDF as a function of density and moisture content. Wood and fiber science 37(2): 314-326.
10. Guo, X., Li, R., Cao, P., Ekevad, M., Cristovao, L., Marklund, B., Grönlund, A., 2015: Effect of average chip thickness and cutting speed on cutting forces and surface roughness during peripheral up milling of wood flour/polyvinyl chloride composite. Wood Research 60: 147-156.
11. Kopecký, Z., Hlásková, L., Orlowski, K.A., 2014: An innovative approach to prediction energetic effects of wood cutting process with circular-saw blades. Wood Research 59(5): 827-834.
12. Kopecký, Z., Hlásková L., Solař, A., Nesázal P., 2019: Cutting forces quasi-orthogonal CNC milling. Wood Research 64(5): 879-890.
13. Krauss, A., Piernik, M., Pinkowski, G., 2016: Cutting power during milling of thermally modified pine wood. Drvna Industrija 67(3): 215-222.
14. Król, D., 2008: Thermal destruction of hazardous waste - copper and lead emissions. Archives of Waste Management and Environmental Protection 7: 43-50.
15. Kuvik, T., Krilek, J., Kovác, J., Štefánek, M., Dvorak, J., 2017: Impact of the selected factors on the cutting force when using a chainsaw. Wood Research 62: 807-814.
16. Macko, M., Tyszczuk, K., Śmigielski, G., Mroziński, A., 2018: Utility of an unitary shredding method to evaluate the conditions and selection of constructional features during grinding. In: MATEC Web of Conferences, Proceedings of the Machine Modelling and Simulations, Sklené Teplice, Slovak Republic, 5–8 September 2017; EDP Sciences: Lez Ili, France, 2018; Vol. 157, 05016: 1-7.
17. Mandić, M.D., Porankiewicz, B., Danon, G.J., 2015: An attempt at modelling of cutting forces in oak peripheral milling. BioResources 10(3): 5489-5502.
18. Manzone, M., 2015: Energy consumption and CO2 analysis of different types of chippers used in wood biomass plantations. Applied energy 156(C): 686-692.
19. Narlıoğlu, N., Salan, T., Çetin, N.S., Alma, M.H., 2018: Evaluation of furniture industry wastes in polymer composite production. Mobilya ve Ahşap Malzeme Araştırmaları Dergisi 1(2): 78-85.
20. Orłowski, K., Ochrymiuk, T., 2017: A newly-developed model for predicting cutting power during wood sawing with circular saw blades. Maderas. Ciencia y tecnología 19(2): 149-162.
21. Orlowski, K.A., Ochrymiuk, T., Atkins, A., Chuchala, D., 2013: Application of fracture mechanics for energetic effects predictions while wood sawing. Wood Science and Technology 47(5): 949-963.
22. Pavlov, A.K., 2019: Factors of supply chain development in the market of furniture products in Russia. In Логистика: современные тенденции развития, Pp 299-303.
23. Porankiewicz, B., Axelsson, B., Grönlund, A.A., Marklund, B., 2011: Main and normal cutting forces by machining wood of *Pinus sylvestris.* BioResources 6(4): 3687-3713.
24. Porankiewicz, B., Goli, G., 2014: Cutting forces by Oak and Douglas fir machining. Maderas. Ciencia y tecnología 16(2): 199-216.
25. Pritchard, J., Ansell, M.P., Thompson, R.J.H., Bonfield, P.W., 2001: Effect of two relative humidity environments on the performance properties of MDF, OSB and chipboard. Wood Science and Technology 35(5): 405-423.
26. Reczulski, M., 2015: Analysis of the construction and operation of system wood chipping and transfer chips. Wood Research 60(4): 671-678.
27. Rydzkowski, T., Michalska-Pożoga, I., 2016: Analysis of intensity of changes in the moisture content of wood chips in the production of wood polymer composites during drying and storage processes. Wood Research 61(3): 457-464.

28. Shahid, L.A., Amjad, N., Siddhu, M.A.H., 2019: Adaptation and performance evaluation stof a tractor operated wood chipper shredder. Pakistan Journal of Agricultural Research 32(1): 197-204.
29. Szpica, D., Czaban, J., 2014: Operational assessment of selected gasoline and LPG vapour injector dosage regularity (Benzino ir suskystintu duju garu dozavimo reguliarumo purkstuku operacinis vertinimas). Mechanika 20(5): 480-489.
30. Warguła, Ł., Adamiec, J. M., Waluś, K. J., Krawiec, P., 2018: The characteristics analysis of torque and rotation speed of working unit of branch grinder-introductory research. In: MATEC Web of Conferences, Proceedings of the Machine Modelling and Simulations, Sklené Teplice, Slovak Republic, 5–8 September 2017; EDP Sciences: Lez Ili, France, 2018; Vol. 157, 01021: 1-8.
31. Warguła Ł., Wojtkowiak D., Waluś K. J., Krawiec P., Wieczorek B., 2017: The analysis of the efficiency of the control system of wood chipper's driver with spark-ignition engine based on Skoda combustion engine 1.4 59kW., Transport Means 2017. In: Proceedings of the 21st International Scientific Conference, September 20-22, 2017, Juodkrante, Lithuania. Part 2: Pp 452-458.
32. Wasielewski, R., 2019: The use of engineered wood wastes for energy production. Archives of Waste Management and Environmental Protection 21(1): 1-8.
33. Wasielewski, R., Bałazińska, M., 2017: Energy recovery from waste in the aspect of electricity and heat qualification as coming from renewable Energy sources and participation the system of emissions trading. Ecological Engineering 18(5): 170-178.
34. Yu, S.T., Yang, C.M., Ren, C.Q., Luo, G., 2012: Cutting force analysis of large branch crusher based on the finite element. In Applied Mechanics and Materials 152: 900-905.

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