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DETERMINING THE COEFFICIENT OF FRICTION OF WOOD-BASED MATERALS FOR FURNITURE PANELS IN THE ASPECT OF MODELLING THEIR SHREDDING PROCESS

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ABSTRACT

In order to improve the power selection of the drive unit for the shredding machines, the authors determine the values of friction coefficients used in the cutting force models. These values consider the friction between steel and such wood-based materials as chipboard, MDF and OSB. The tests concern laminated and non-laminated external surfaces and surfaces subjected to cutting processes. The value of the coefficient of friction for the tested materials is in the range: for the static coefficient of friction 0.77-0.33, and for the kinetic coefficient of friction 0.68-0.25. The highest values of the static and kinematic coefficient of friction were recorded for MDF (non-laminated external surface) and they were equal respectively: 0.77 and 0.68. In turn, the smallest values of the discussed coefficients were recorded for chipboard (laminated external wood-base surface), which were at the level of 0.33 and 0.25, resp.

KEYWORDS: Static friction coefficient, kinetic friction coefficient, MDF board, OSB board, chipboard, carpentry waste.

INTRODUCTION

Many processes that use wood and wood-based waste need shredding of these materials. This improves their transport, storage and processing. The re-use of waste wood and wood-based products from production or from the use of products, contributes to reducing both wood waste and deforestation in various geographical areas. At the same time, it is important to use economically efficient machines with a low environmental impact. The increase in consumption worldwide (Blühdorn 2017, Zaharia and Zaharia 2015) contributes to the increase in the amount of waste (Fan and Meng 2020), including: post-consumer waste (Ihnat et al. 2020), used furniture, packaging (Czarnecka-Komorowska and Wiszumirska 2020, Czarnecka-Komorowska et al. 2018). Processes managing wood-based waste often use shredding machines (Warguła and Kukla 2020, Zhang et al. 2019, Yu et al. 2012), as this facilitates the processes of storage, transport (Reczulski 2015, Gałęzia 2013, Warguła et al. 2020b) and processing, for example: combustion (Rabajczyk 2020, Kajda-Szcześniak and Jaworski 2018, 2019, Spîrchez et al. 2019, Chen 2015), composting (Knitter et al. 2019) including biomass gasification (Sheth and Babu 2010), biochars production (Kosakowski et al. 2020), pellet production (Saosee et al. 2020, Macko and Mroziński 2018, 2019, Ibrahim et al. 2018) and briquettes production (Garrido et al. 2017) or reuse in the production of furniture boards (Ihnát et al. 2017, 2018, Souza et al. 2018).

In these processes, the chippers are mostly mobile machines, powered by combustion engines (Laitila and Routa 2015, Han et al. 2015, Spinelli and Magagnotti 2013). In the case of such machines, it is advantageous to choose a drive unit with no more power than required, as larger internal combustion engines are characterized by an increase in fuel consumption and exhaust gas emissions. This is also important due to the ongoing process, which in essence is not continuous (Warguła et al. 2019). Shredding is usually a periodic-change process in which the machine load results from the frequency of waste delivery (Warguła et al. 2020b). Designing innovative machines shredding wood and wood-based materials is carried out to reduce: environmental impact (Waluś et al. 2018) and operating costs (Warguła and Krawiec 2020). The most popular solutions include the use of: cutting mechanisms, characterized by lower cutting force and increased durability (Guerrini et al. 2019, Macko et al. 2018a,b, Czerniak et al. 2016, Reczulski 2016, 2018), innovative control processes - improving adaptation to conditions of use (Warguła et al. 2020a,d), but also powering engines with fuels alternative to gasoline (LPG and CNG) (Warguła et al. 2020c,e, Dziewiatkowski et al. 2020, Szpica 2018).

Designing machines with a drive unit selected efficiently for the required shredding processes requires precise models of cutting force. These are used, for example, during designing: circular saw (Kopecký et al. 2014, Orłowski et al. 2013, Porankiewicz et al. 2011), a band saw (Chuchała and Orłowski 2018, Orłowski and Ochrymiuk 2017), a chain saw (Kuvik et al. 2017), a large size crusher (Yu et al. 2012), a milling machine (Kopecký et al. 2019, Durkowić et al. 2018, Krauss et al. 2016, Pinkowski et al. 2016, Mandić et al. 2015, Guo et al. 2015, Džinčić et al. 2012). In the event of significant overcapacity, the machine will be characterised by inefficient operation and increased emissions of air pollutants. On the other hand, insufficient power of the drive unit may hinder, and in extreme cases prevent the shredding process (e.g. by blocking the cutting mechanism). The creation of a mathematical model requires knowledge of the values of the coefficients on which it is based, with the greatest accuracy being achieved by experimentally determining the values sought. The results of previous research work on cutting force (Warguła and Kukla 2020) suggest that the shredding process of wood-based panels can essentially be divided into two parts. In the first part, the material is crushed by compacting it. However, the actual part of the process, i.e. cutting, takes place only after the tool has been recessed to a certain depth. This is due to the properties of the cut furniture boards, which are a wood-based material, as schematically presented in Fig. 1. Considering the conclusions from previous studies, it was noted that the cutting process of the discussed wood-based and wooden materials is similar to that of other materials of plant origin. Therefore, it is reasonable to use available theoretical models of cutting materials of plant origin describing this phenomenon, such as the one described in Eq.1:

$$F = g\sigma + \frac{E}{2} \cdot \frac{h^2}{H} [\tan\beta + \mu\sin^2\beta + \mu'(\mu + \cos^2\beta)], \tag{1}$$

where: F is the pressure force per blade length unit, g is the thickness of the blade, σ is the stress in the material created during cutting, E is Young's modulus of the material to be cut, h is the thickness of the layer of material to be crushed with the knife, H is the total height of the material, β is the angle of application of the knife blade, μ is the coefficient of internal friction, μ' is the coefficient of friction between the knife blade material and the material to be cut (Kanafojski and Karwowski 1976).

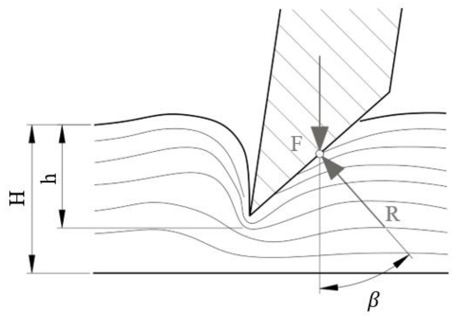

Fig. 1: Force acting on the knife edge at the beginning of the cutting process of plant-based material; H- thickness of the material being cut, h - thickness of the crushed layer, R - reaction force of the material being cut; prepared based on (Kanafojski and Karwowski 1976).

Of course, it is possible to numerically model different values of the friction coefficient μ' corresponding to different values of the cutting depth h. This will allow to take into account the layered structure of the material. This is necessary because each of the layers (in general) may have various properties - including the different values of coefficient of friction.

The main objective of the conducted research is to develop innovative solutions for drive systems of low-power internal combustion chippers for the purpose of shredding wood material and its derivatives, especially wood-based panels. Therefore, it is necessary to precisely define and model the values of forces which must be transferred by cutting mechanisms of machines shredding furniture waste. As a result, this will also translate into the determination of the mechanical power requirements of their drive systems. The proper selection of the drive unit, without too much power reserve, translates into measurable environmental and economic benefits related to the energy saving during the implemented process. This is why it is important to conduct research in the discussed direction. In the presented model (1), only the first component represents a useful force, which is necessary to carry out the cutting process. Due to the large variety of plant-based materials, its value can only be determined based on experiments. Research work is currently under way on this issue. The second segment of Eq. 1 is related to cutting resistances not directly related to the process itself, i.e. crushing of the material, internal friction and friction between the blade and the material being cut. The results presented in this article are related to the experimental determination of coefficients of the described model. The literature provides values of friction coefficients of wood-based materials (Kazlauskas et al. 2020, Stasiak et al. 2020, Bejo et al. 2000), but does not consider all materials presented in this article and does not consider all surfaces with which the cutting knife may come into contact during the shredding process.

The value of the friction coefficient between: wood-based materials, a wood-based and wood-based materials and/or the cutting tool can depend on many factors. The value of the friction coefficient between two wood-based materials may change, for example, with an increase in contact pressure (an increase in contact pressure causes a decrease in the kinematic and static friction coefficient) (Bejo et al. 2000). Wood moisture contributes to the increase of the static and dynamic friction coefficient (Aira et al. 2014, Seki et al. 2013). The average coefficient of friction between the cemented carbide and the wood surface increased with increasing moisture below the fiber saturation point (FSP). However, an increase in the amount of free water may lead to a more significant decrease in the friction coefficient (Li and Zhang 2019). The arrangement of wood fibers may result in even a twice higher value of the friction coefficient (Aira et al. 2014). The kinematic parameters of the contact, e.g. velocity, also affect the value of the kinetic friction coefficient, however, the available studies for a variety of wood and wood-based materials do not show unequivocal relationships (Li et al. 2013). The value of the dynamic friction coefficient, e.g. during cutting with a steel tool or sintered carbides, can be reduced by applying various types of coatings, e.g. carbon (Karczewski et al. 2012), carbon and titanium (Kaczorowski and Batiry 2008), CrxNy (Djouadi et al. 2000), TiAlN/a-CN (Czarniak et al. 2020) coatings. With the properties of, for example, a cutting tool, the coefficients of dynamic friction of wood-based and wooden materials are affected by their roughness (Xu et al. 2014). The value of the friction coefficient is influenced by many parameters, the authors of the article presented research for a classic tool set in grinders made of tool steel. The speed of the process corresponded to the actual operating conditions of the tested machines, which can range from 40 rpm to 2500 rpm (Huber et al. 2017, Warguła and Kukla 2020, Warguła et al. 2020f) and the ambient temperature similar to that available in the production halls of carpentry workshops.

MATERIALS AND METHODS

Wood-based materials samples preparation

Measurements in this study were carried out for 11 sample types. Using mechanical processing, individual samples of 40 × 15 cm were cut out from boards supplied by commercial suppliers. Depending on the type of board, they differed slightly in thickness, but this parameter does not affect the measurement results.

In the case of a wood-based panel, the external surface was tested in its nominal condition (i.e. the surface condition as the material is immediately after purchase, without any additional treatment likely to change its properties). In the case of MDF, the external surface was tested in its nominal laminated and non-laminated condition. Additionally, experiments were carried out on the surface created after mechanical cutting off of the selected plane of the tested material. In the case of chipboard, its external and side surfaces were tested in their nominal condition and the surface created after mechanical cutting off part of the material. In addition, the external surface in its nominal condition for the second type of laminated chipboard (porous structure) was also tested. For OSB, the external surface in its nominal condition, the side surface after mechanical cutting of the material and the surface after removal of the cover layer were also tested. In the last case, it was necessary to prepare the surface for testing by partial smoothing. The aim of this treatment was to remove protruding parts of the chips with a grinding wheel (because they were crushed or broken during the tests, making it impossible to carry out the experiment) and not to obtain a smooth surface structure. It was decided to leave the boards nominal thickness so that it is not necessary to cut them wide. The characteristics and determinations of the individual samples are presented in Tab. 1. The markings introduced in Tab. 1 have been consistently maintained throughout the article. The individual surfaces are shown in Fig. 2.

Temperature and humidity affect the results of friction tests (Park et al. 2011). Thus, prepared test samples were conditioned at temperature of 20°C and humidity of 65% so that they reached a moisture content (MC) of 10% ± 0.1%. For this purpose, a climatic chamber was used. The moisture content was checked with a Mettler Toledo moisture analyser during conditioning until the desired value was obtained. The measurement consisted in precise weighing of the sample (± 0.001 g) and simultaneous drying (change of MC from measured value to oven-dry).

Tab. 1: Characteristics and markings of individual samples.

Sample No.	Material type	Surface
1	Chipboard	Laminated external wood-base
2	MDF	Laminated external
3	MDF	Non-laminated external
4	MDF	After mechanical cut
5	Chipboard	Laminated external porous
6	Chipboard	Non-laminated external
7	Chipboard	After mechanical cut
8	Chipboard	Side
9	OSB	After mechanical cut
10	OSB	External
11	OSB	After mechanical removal of the cover layer and smoothing

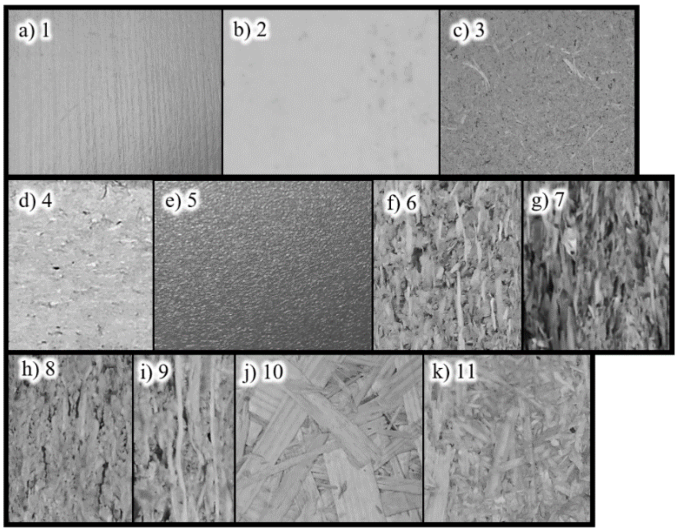

Fig. 2: View of individual tested surfaces; a) sample 1, b) sample 2, c) sample 3, d) sample 4, e) sample 5, f) sample 6, g) sample 7, h) sample 8, i) sample 9, j) sample 10, a) sample 11.

Chipper knives material

A lot of research work can be indicated in the field of surface roughness and topography of contact surfaces, but the exact relationship between surface roughness and friction has not yet been defined (Sedlaček et al. 2009, Meine et al. 2002). Moreover, there are a number of parameters that describe the surface profile. A maximum of 17 parameters are currently being used for this purpose (Meine et al. 2002). So far, however, no single definition of roughness describes the surface profile in a complete way. As a result, quite different surface topographies can have the same roughness value (Meine et al. 2002, Bhushan 1999). However, test results are available to indicate the relationship between roughness and coefficient of friction in dry conditions (without lubricants) (Al-Samarai et al. 2012). Therefore, tests have been performed to determine the surface roughness of cutting plates made of metallic material. However, when interpreting them, the above-mentioned comments should be considered.

The test uses cuboidal plates made of HADOX steel, type 500. It is the same type of material that is used for knives in a cylindrical chipper. The plates were cut out by machining. Before the test, their surface was prepared by rough cleaning with sandpaper and degreasing with a high percentage solution of technical alcohol. The material in this condition corresponds to brand new knives used in chippers. It should be stressed that they are subject to relatively fast wear as a result of the impact character of this type of machines. The condition of the knives' surface may affect the friction coefficient measurements.

The roughness was measured with a Jenoptik IMG Hommel Tester T1000 profilometer using a T1E sensor within a measuring range of 80 µm. The measuring distance was l_t = 4.8 mm and the elementary distance was l_c = 0.8 mm. Five measurements were taken at different places of the prepared plate. The recorded surface profiles are shown in Fig. 3. The collected results concerning: the highest roughness height R_{max}, the highest roughness height according to the measured 10 highest profiles R_z and the mean arithmetic deviation from the mean line R_a are shown in Tab. 2.

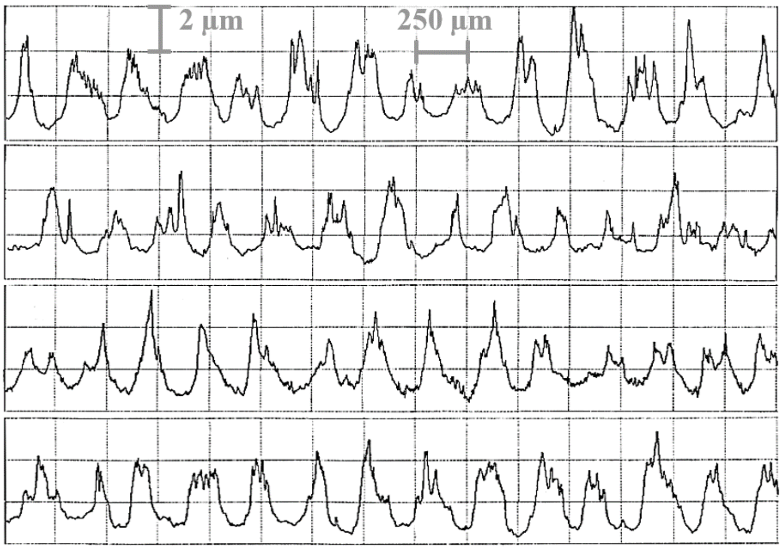

Fig. 3: Selected surface profile shapes of tested metal plates.

Tab. 2: Measured parameters related to the roughness of metal plates.

R_{max} [µm]	R_z [µm]	R_a [µm]
5.48	4.60	0.704
5.77	4.75	0.943
4.37	3.75	0.638
5.01	3.95	0.729
5.03	4.14	0.956

Kinetic friction tests

The research was carried out to determine the coefficient of friction between panels made of wood-based materials and the metal alloy which is used for the production of chipper knives. The determination of the kinetic coefficient of friction took place on a specially prepared station according to the scheme presented in Fig. 4. The tested sample (1) was fixed to the base. A rectangular element made of the used metal alloy (2), which was additionally loaded with mass (3), was placed on it. The total mass of the cuboidal block of the tested metal alloy and the weight was m = 39.5 kg. The hydraulic cylinder (5) was equipped with a force transducer (4), (C9C 1 kN by HBM) which registered this physical value F(t) cooperating with a measuring amplifier (Spider 8 by HBM) and a PC class computer. Hydraulic system cooperating with the actuator allowed to provide a constant value of the actuator's displacement velocity independent of the applied load. The force was applied to the element being moved axially in order to ensure its linear movement, despite this the position of $x(t)$ of the tested element was controlled during the experiment. The actuator's displacement velocity was v = 22 mm·s^{-1}. It was selected in such a way that for set load value, for the largest possible group of materials there was no stip-slick phenomenon.

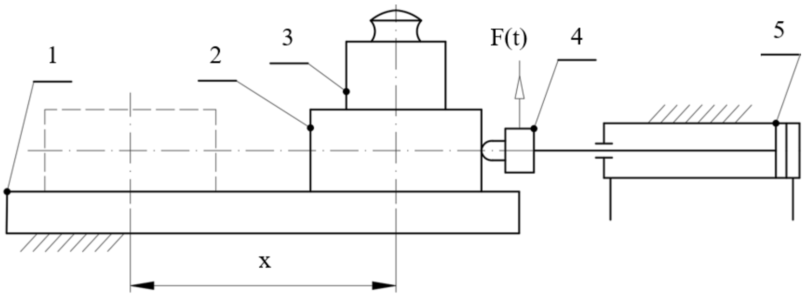

Fig. 4: Scheme of the system for determining the kinetic coefficient of friction; 1 - wood-based panel test sample, 2 - metal alloy test, 3 - mass, 4 - force transducer, 5 - hydraulic cylinder.

In the tests described, the force vs displacement can be presented as one of the three characteristic curve types, shown in Fig. 5. In the case shown in Fig. 5a, there is the stick-slip phenomenon, which is the effect of cyclic overpowering of the force causing the movement and the resistance force of this movement. In this case the maximum friction force F_s was determined from the first extreme of the recorded force. The average friction force F_k was calculated from the sum of the successive minimum and maximum extremes of the measured signal. In the case shown in Fig. 5b, the value of the maximum friction force was determined in a similar way. The average value of the friction force F_k was taken as the arithmetic mean from the measured signal of the friction force course. The sought value F_k for the case from Fig. 5c was determined in the same way, except that for this case it was impossible to define unambiguously the maximum friction force, because the point of occurrence F_s was not a local extreme of the recorded force course. The described test methodology was based on ASTM D2394: 2011.

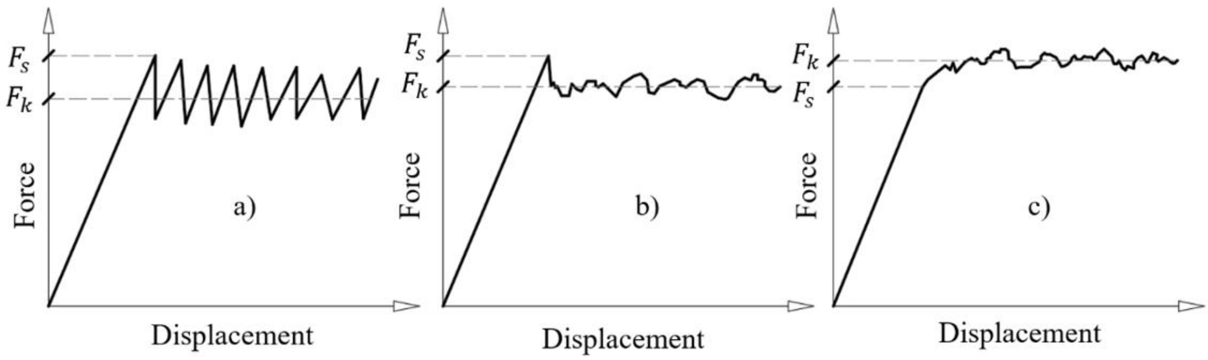

Fig. 5: Nature of the recorded force depending on the friction process; a) the occurrence of the stick-slip phenomenon, b) movement with a clear maximum force value, c) movement without a clear maximum force value.

Based on the determined values: F_s and F_k, static μ_s and kinetic μ_k coefficients of friction were calculated, according to Eqs. 2 and 3:

$$\mu_s = \frac{F_s}{N}, \quad (2)$$

$$\mu_k = \frac{F_k}{N}. \quad (3)$$

In order to analyse the values of these two coefficients, the values of their ratio R have also been determined in accordance with Eq. 4:

$$R = \frac{\mu_s}{\mu_k}. \tag{4}$$

For each of the 11 types of samples 10 experiments were carried out. The arithmetic mean of all measurements for each type of material was taken as the estimator of the static μ_s and kinetic μ_k coefficient of friction values sought. The standard deviation of the arithmetic mean was taken as the estimator error.

RESULTS

The results for a single measurement are shown in Fig. 6, while the selected range for the entire measurement series is shown in Fig. 7. The results of the determined values are shown in the Tab. 3, while their graphical interpretation is shown in Fig. 8.

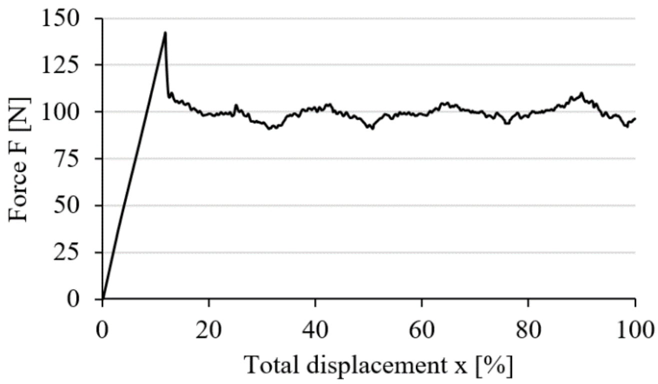

Fig. 6: Selected test result recorded for a single measurement; sample number 2 (MDF, laminated external surface).

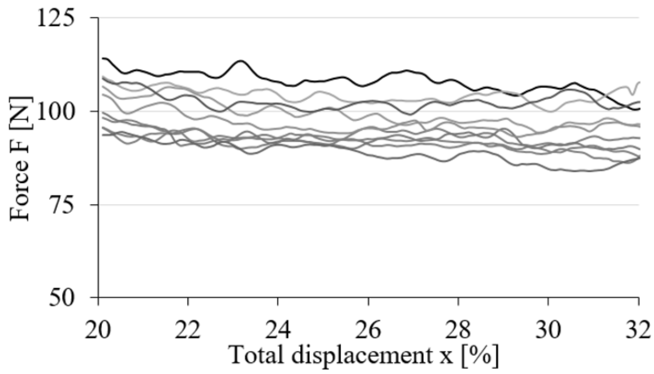

Fig. 7: Set of results of 10 measurement tests for a selected range of experiments (individual colours correspond to successive repetitions); sample number 1 (Wood-based panel, laminated external surface).

Tab. 3: Determined values of static μ_s and kinetic μ_k coefficient of friction and their relationship R; AVG – mean value, SD – standard deviation.

Sample No.	μ_s		μ_k		$R = \mu_k/\mu_s$
	AVG	SD	AVG	SD	
1	0.33	0.02	0.25	0.02	0.75
2	0.38	0.02	0.25	0.01	0.67
3	0.77	0.02	0.68	0.05	0.89
4	0.64	0.02	0.50	0.03	0.79
5	-	-	0.35	0.03	-
6	0.56	0.01	0.46	0.02	0.82
7	0.60	0.01	0.43	0.03	0.72
8	0.55	0.03	0.44	0.04	0.81
9	0.51	0.03	0.38	0.02	0.74
10	0.60	0.06	0.42	0.05	0.70
11	0.62	0.03	0.51	0.04	0.83

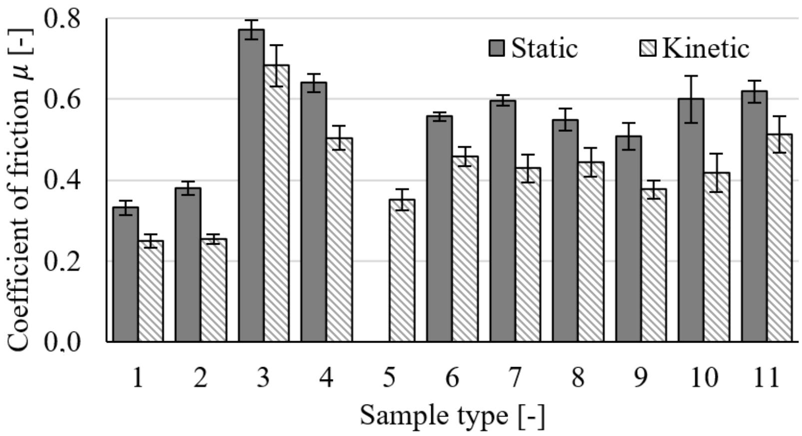

Fig. 8: Results of static μ_s and kinetic μ_k coefficient of friction for individual sample types; error bars are ± standard deviation.

DISCUSSION

The static μ_s and kinetic μ_k coefficient of friction values determined indicate that the former is always greater. Their ratio R is 0.77 on average, with the greatest value equal to 0.89 for sample number 3 and the smallest value equal to 0.67 for sample number 2.

Within MDF samples the lowest coefficients of friction (both static and kinetic) are for the laminated surface. Higher values were noted for the cut surface and the highest values for the non-laminated (side) surface. The increase in the static coefficient of friction μ_s from minimum to maximum for this type of material was 39% and for the kinetic coefficient of friction μ_k it was 51%.

The test results for chipboard are characterized by similar values of friction coefficients in the range of non-laminated surfaces (type 6-8 samples). The biggest difference (8%) in the static μ_s coefficient of friction was observed for samples 7 and 8, and the biggest difference in the kinetic μ_k coefficient of friction (6%) was observed when comparing the results for samples 6 and 7. Due to the nature of the process, it was not possible to determine the static μ_s coefficient of friction for sample number 5, while the kinetic μ_k coefficient of friction was 0.35 and was 18% lower than the next value for this type of material (samples type 5 and 7).

Interestingly, in the case of OSB, the surface created after mechanical cutting of the material had the lowest friction coefficient value. A higher value was recorded for the external surface in its nominal condition, and the highest value of the coefficient of friction was recorded for the internal surface (after removing the top of the material). The difference between the extreme values was 18% for the static coefficient of friction μ_s and 26% for the kinetic coefficient of friction μ_k (type 9 and 11 samples).

Test results for materials with a laminated surface (type 2 and 5 samples) compared to non-laminated surfaces (type 3 and 4 and 6-8 samples respectively) indicate lower values of both coefficients of friction. This is of course due to the different type of material and other parameters of the cooperating surfaces, which however has important implications for the cutting process. The laminate (lower coefficient of friction) may be located only in the small top part of the furniture board's cross-section, while the main part of it consists of a compressed wood-base material (higher coefficient of friction). Therefore, in addition to, for example, the geometry of the blade, the structure of the material itself is also a source of variation in the cutting force value during the process.

The recorded values of static μ_s and kinetic μ_k coefficient of friction and their ratio R can be compared, for example, to tests related to the determination of the coefficient of friction of spruce lumber, for different surface states resulting from the sample preparation method (Park et al. 2011). The range of determined values and in particular the values of the ratio R can be considered to be similar.

CONCLUSIONS

Within the framework of the described research works, the force necessary to displace 11 types of samples from wood-based materials and metal material used for the production of cutting elements for chippers with combustion engines was measured. The samples differed in the type of material and surface condition. Based on the measured force course, static μ_s and kinetic μ_k coefficient of friction and their ratio R were determined, which were subsequently analysed. The data collected will be used, among other things, to model the cutting force during the shredding process of wood-based furniture boards. This will be used to determine the demand for mechanical power of low-power drive systems of chippers with combustion engines, which will allow to propose new technical solutions in this aspect. The main conclusions resulting from the research work can be presented as follows: *(1)* For the accepted parameters of the experiment (movement speed v = 22 mm·s^{-1}, loading mass m = 39.5 kg), an irregular "stick-slip" movement occurred for sample number 10 (OSB external surface layer in nominal condition). *(2)* For the accepted parameters of the experiment (motion velocity v = 22 mm·s^{-1}, loading mass m = 39.5 kg) the recorded movements did not allow to define the maximum friction force, because the point of occurrence F_s (force value at the moment of static/kinetic transition) was not a local extremity of the recorded movements (case from Fig. 5c) for sample number 5 (laminated external porous chipboard). *(3)* The coefficient of friction between the machine knife and the material to be shredded is not constant. This is, among other things, due to: the heterogeneous structure of the material, the surface profile of the material before and during the shredding process and its composite structure (different materials included in the furniture board and surface modifiers). *(4)* The differences in the value of the friction coefficient may vary from a dozen to several dozen percent. As a result, the demand for the drive torque for the chipper's working mechanism will change during the shredding process. This is important because the working section of this machine is anyway subjected to high dynamic loads of an impact character due to its nature of work.

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