The research on the characteristic of the cutting force while chipping of the Caucasian Fir (\textit{Abies Nordmanniana}) with a single-shaft wood chipper

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Abstract. Waste management in a selective manner requires the collection of waste, among others, also large-scale. In Poland, in January and February, the collection of biodegradable waste is carried out – Christmas trees. This process is carried out by collecting from the real estate the whole trees, and then transporting them to the utilization place, where they undergo chipping processes. The article discusses the subject of estimating the cutting force when chipping a single-shaft wood chipper of the Caucasian Fir (\textit{Abies Nordmanniana}). The obtained results of the loads characteristics and values of forces will enable the design of effective chipping machines. They can also help improve the efficiency of the selective waste collection process i.e. Christmas trees by developing mobile chipping machines mounted on waste collection vehicles. They will allow to limit the number of operations in the waste treatment process to collect and transport the shredded biodegradable mass to the processing stations.

1. Introduction
One of the contemporary problems of urban agglomerations is the waste management. Selective waste management is an advantage for such an economy and the natural environment. In segregated waste there are large-size waste of floral origin. In the period of January and February in Poland, these are Christmas trees among which one can distinguish: spruce (\textit{Picea abies}), silver spruce (\textit{Picea pungens}), Caucasian fir (\textit{Abies nordmanniana}), Korean fir (\textit{Abies koreana}) and pine (\textit{Pinus sylvestris}). For these wastes, the following recycling processes should be applied: waste collection, transport, processing and the use of processed waste. The classic course of the process is waste collection and transport to the processing point, where the waste is applied to: briquetting [1–3], composting [4] or combustion [5, 6]. The transport of trees in one piece increases the volume of transported raw material and requires waste pressing systems to compact them. In addition, the waste requires another loading operation for the grinding machines. An advantageous solution may be the use of crushing machines in selective waste collection vehicles. The crushing of such waste takes place in a few seconds [7] and should not significantly affect waste collection time, and allows to reduce the number of operations and machines used, i.e. for tree loaders for shredders. Technical, technological and organizational conditions for obtaining chips and transport from forest areas were analyzed in the literature indicating that the currently used methods of harvesting, grinding and transporting forest biomass in the form of chips are very efficient from the point of view of the energy balance [8]. However, their efficiency can be increased by locating the cutting area closer to the power plant [9]. This suggests that the cost of transport
is one of the basic costs in obtaining wood chips. The effectiveness of obtaining wood chips in urban areas by shredding Christmas trees wood waste can be improved by using trucks with a start-stop system [10], and with crushing machines with non-road internal combustion engines [11, 12] equipped with adaptive systems depending on exploitation conditions [13, 14]. The other way of improving the effectiveness in the analysed area is the application of electric drives in the vehicle as well as shredding machine, where in case of electric powered chain saws saws the efficiency was higher than of those powered by combustion engines [15]. There are literature available on the improvement of the efficiency of grinding and production of chips of adequate quality for further processes [16] and including methods for measuring the energy consumption of the grinding process [17]. The efficiency of the shredding process also depends on the selection of machine parameters such as: settings [18] and type of shredder [19], type and quality of chips and drive unit for the object to be grinded: type, moisture and wood size [20]. In the literature, the results of power demand research are available during the crushing of plant biomass: cereal straw [21], corn straw, sylphion stems (cup-plant) [22], willow shoots [23], poplars, Jerusalem artichoke, miscanthus [24], energy crops [25]. There are no studies on the energy consumption of the processes of shredding the Christmas trees. Among the useful characteristics of the shredding processes [26], it is advantageous for the cost evaluation to determine the torque \( M_o \) (1), grinding time \( t \), shredder power \( P \), energy consumed for shredding \( E \) (2):

\[
M_o = r \cdot F = \frac{P}{\omega} \tag{1}
\]

where \( r \) – force radius vector (m), \( F \) – active force (N), \( \omega \) – angular velocity of cutting parts (rad s\(^{-1}\)) and:

\[
E = P \cdot t = F \cdot r \cdot \omega \cdot t \tag{2}
\]

An important aspect is the evaluation of the operating costs of the developed construction and process solutions. Chips are subject to various commercial units: m\(^3\) chipped volume, dry metric tonnes or MWh, hauliers per raw tonnes or m\(^3\) chipped volume and the company supplying the chips to the heating plant most often per delivered MWh [27], which should be noted during the cost estimation [28]. In order to select the characteristics of the shredding machines and their drive units and to estimate the cost of the process of collecting the post-harvest trees waste, tests were carried out on the cutting force characteristics during grinding with a single-shaft shredder the Caucasian Fir (\textit{Abies Nordmanniana}). Distinctive impact of the surface area of the grinded material and the type of grinded over ground part of the tree can be noticed on the nature of the grinding process.

2. Test stand
The research was carried out on a test stand that allows to perform the studies on wood shredding process [29]. The stand was built on the basis of the MQS2800 Macalister electric grinder, intended for crushing wood (figure 1). A chipping unit consisting of an electric motor, belt gear, double epicyclical gear and a working unit was excluded from it. In order to enable the study of kinematic and dynamic features of the grinding process, the isolated unit was equipped with measuring devices (figure 2). The torque was measured using a universal torque meter designed by the team at the Chair of the Basics of Machinery Construction at Poznan University of Technology. The Megatron MOB 2500/5 / BZ / N encoder was used to record temporary changes in the angular velocity of the working shaft of the grinding unit. The results of torque measurements were recorded in the proprietary computer program that is an integral part of the station.

3. Research object
The branches and boughs of the Caucasian Fir (\textit{Abies Nordmanniana}) with a moisture content of approximately 4 % and a characterized cross-section were the objects of the research. The logs were not subject to the research process due to the limitations of the test stand: size of the feeding channel (up to 300 mm) and the permissible value of the torque meter load (up to 200 Nm).
4. **Research results**

The preliminary studies of kinematic and dynamic features of the chipper working unit were carried out, determining the values of its torque. In the first test, these values were measured without the system load (figure 3).

In subsequent attempts, the process of branch crumbling (table 1) and boughs (table 2) was carried out paying attention to cross-sectional views. The exemplary torque characteristic is shown in figure 4. The average rotational speed of the working unit during the grinding process was about 50 rpm.
Figure 3. The torque characteristics in a function of time without the load on the working unit: a – start-up, b – stable work without external load, c – switch of the system.

Figure 4. The torque characteristics in a function of time of a working unit, while grinding branches of a core diameter of 15 mm.

Table 1. The results of the demand for the torque of the drive during the crushing of the branch Caucasian Fir (Abies Nordmanniana) with defined geometry.

| Kind of sample | The average core diameter (mm) | Maximum torque value during grinding | Standard deviation from the maximum value |
|----------------|--------------------------------|--------------------------------------|------------------------------------------|
| 5              | 15                             | -5                                   |                                          |
| 10             | 38                             | -10                                  |                                          |
| 15             | 75                             | -20                                  |                                          |
| 17             | 130                            | -30                                  |                                          |
Table 2. The results of the demand for the torque of the drive during the crushing of the branch Caucasian Fir (Abies Nordmanniana) with defined geometry.

| Kind of sample | The average core diameter (mm) | Maximum torque value during grinding | Standard deviation from the maximum value |
|----------------|-------------------------------|-------------------------------------|------------------------------------------|
|                | 10                            | 62                                  | -8                                       |
|                | 15                            | 84                                  | -20                                      |
|                | 17                            | 130                                 | -30                                      |

5. Results analysis

The actual dynamic characteristics of the torque of the MQS2800 Macalister wood shredder’s working unit are characterized by variability and are subject to signal interference. However, the main nature of the changes is observable. The unloaded working unit generates a torque oscillating in the range of 0 to 10 Nm, due to the construction, which is unbalanced as shown in figure 3, and additionally is exposed to changes in imbalance associated with loss on blade created during exploitation. The grinding process generates a unique characteristic, which is the result of the process of cutting orthotropic plant materials whose structure is anisotropic. When grinding the above-mentioned sample, it is possible to determine the characteristics of the torque changes depending on the geometry of the material being crushed (figure 5).

The stand made it impossible to examine the Caucasian Fir logs (Abies Nordmanniana), which significantly limited the application of research results to the assessment of the characteristics of shredding the post-Christmas trees. However, the tests carried out indicate that the value of torque increases as the cross-section of the crushed branch or bough increases. At 17 mm core diameter of the test samples, the results are convergent for branches and logs suggesting that the main character of the load in the grinding process is affected by the diameter of the thickest part of the tree. This may suggest that when cutting trees with logs, branches and boughs, the log will be the main load during the grinding. However, in order to confirm this conclusion further research on the site enabling the shredding of also the logs of post-Christmas trees is necessary.

Figure 5. Torque changes characteristics during grinding the branches and boughs of Caucasian Fir (Abies Nordmanniana) in a function of cross-section: blue – branches, orange – boughs.
However, further research on the grinding machinery mounted on the selective waste collection vehicles is important as it may limit the number of operations in accordance with figures 6 and 7.

Figure 6. The classic process of green waste processing and management in the form of post-Christmas trees.

Figure 7. The process of green waste processing and management in the form of post-Christmas trees after applying innovation in transportation vehicles – focused on indicating improvement of product cycle economy.

6. Conclusion
The conducted experimental and preliminary research have shown that the created test stand allows the study of the characteristics of the working unit of the chipper MQS2800 Macalister, which is a representative of electric chippers intended for households. They also showed that it is insufficient to analyse the process of shredding entire post-Christmas trees. The collected characteristics allow the analysis of shredded samples in terms of their maximum strength values and processes occurring during
cutting in reference to branches and boughs of Caucasian Fir (Abies Nordmanniana). The actual characteristics of the generated torques can be used in the construction strength analysis for the above-mentioned wood waste, simulation models of the durability of the chipper components, i.e. a working unit, gear or drive. The collected characteristics allow also to assess the effectiveness of the shredding process using the construction on the basis of which the test stand was developed. A further area of research is the development of a research methodology of the fragmentation of trees, and resulting from them, the development of grinding equipment dedicated to selective waste collection vehicles, allowing significant savings to be achieved in waste management processes.

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