Simulation of Stress and Strain Analysis on a Delimbing Knife with Replaceable Cutting Edge

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This study focused on stress and strain analysis of the cutting force of a branch knife with a replaceable cutting edge. The replaceable edge forms part of the delimbing head, which is applied to the arms of a mechanical harvester working in forestry. Basic parameters of the knife and head of the harvester with the basic calculations necessary to determine the number of knives based on input parameters, such as wood diameter, woody plants, and determination of the cutting force acting on the cutting knife, were examined. Based on the cutting force and the design of the special cutting knife, a stress analysis and a finite element method (FEM) was performed. This study confirmed the correctness of the selected material to produce the delimbing knife, which was designed using a replaceable cutting edge. The output of the stress analysis is reported.

Keywords: Harvester head; Delimbing knife; Delimbing wood; Stress analyses; Forestry

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INTRODUCTION

The harvester head has an important role in the efficiency and quality of wood processing. The tasks of the harvester head are cutting the wood, delimbing the branch, cutting the tree to the specified length, and storing it at the wood dump. The harvester head consists of a chain or knife feed undercut mechanism. Nowadays the chain mechanism is increasingly used due to minor damage to the wood. The saw is hydraulically driven, has a more robust chain, and higher power per man (Hatton *et al.* 2016; Kováč *et al.* 2017). Today there are many competing harvester heads on the market. The main differences are in the maximum diameter of processed wood, which depends on the robustness of the head, the number of delimbing knives, the type of feed system, and the manner in which the wood is stored. An important factor affecting the separation process is the wear of the cutting edge of the separation knife. The delimbing knife is part of the combine head. Replacing it reduces the efficiency of the machine and thus increases the economic cost of the machine for operation.

Harvester Heads Working Mechanisms

The working mechanisms affecting the operation of a harvester head are cutting (shading), delimbing, feeding mechanism, measuring, loading, and unloading. The delimbing mechanism serves to delimb the branch of wood. In the course of the collecting and transporting operations, the blade part is most subject to wear (Hatton *et al*. 2015). The blades are essentially hyperbolic-shaped knives, placed in the head or on a telescopic boom. Most harvester heads have one solid and two movable knives. Between these knives, the delimbing wood is pulled by feeding rollers at a constant speed of 2 m.s^{-1}, and its branches are cut off. Blade knives should be able to best replicate the shape of the stem (Mikleš *et al*. 2004; Puttock *et al.* 2013; Hatton *et al.* 2015). Harvesting and transport machinery must work in the forest under difficult terrain and climatic conditions. High demands are placed on reliability, operational capability, productivity, durability, and economic efficiency. In operation LH (Forestry, machines working the day in the forest) working today, harvesting-transport machines have experienced developmental shifts from simple to complex machines using a greater range of automation components from computer technology. Harvesting-transport machines can be classified according to different points of view, where one of the main criteria is the number of operations. These operations include: a) single-operation machines that perform one main operation, and b) multi-operation machines that perform at least two main operations.

The multi-operation machines include working machines that are equipped with a multi-operation extraction head. Previous scientific contributions have considered a designed harvester head (multi), which meant that the processing of wood had to do more work operations using a plurality of machines (Khvostov *et al.* 1987; Hatton *et al.* 2015; Cacot *et al.* 2016). In terms of carrying out at least two main operations, their distribution is as follows.

The division according to the method of separation of branches from the trunk involves the three following areas: branching or tumbling branches (especially for bulk separators), milling, which is currently unused, and trimming with branch knives or link chains.

Classification of their distribution according to the method of trunk drive is broken into the following five parts: 1) Towing a special forestry wheeled tractor equipped with a device for grabbing or gripping (*e.g.*, winch, rope); 2) In a linear motion derived from receiving the jaws or a convenient trolley; 3) The drive chain, uses one of the many forces working movement mechanism and is driven by the tension of the head, where the wood is pressed delimbing knives; 4) The feed chain on the harvester head is today used most frequently because of less damage to the wood on the cutting area, and it can also be used with drive rollers, which are the most used method, and are part of the head; 5) A combination of drive rollers and drive chain, where the drive chain is fixed, and the drive tire rollers are movable.

The breakdown of the operations carried out are as follows: delimbing machines that separate the branches from the trunk, grab the tree, and land the trunk. After the wood processing process, the processed tree will be transported for short hauling using its own chassis, stanchion exporter, and hydraulic arm (brought, approached, loaded, and collapsed); and harvesters that are multi-operative machines that shade (felling), partially work (delimbing, debarking), or also transporting it a shorter distance (zoom, load, fold) (Mikleš *et al.* 2004; Kováč *et al.* 2016).

The task of the harvester head, depicted in Fig. 1, is to fell the tree, to delimb the tree, to cut the tree to the specified length, and to place it on the assembly site (dump). Harvester heads differ with respect to the thickness of the treated wood, the shape and the number of delimbing knives, the type of feeding device, the way of measuring lengths and thicknesses, and the arrangement of the cutting part. A typical harvester head (Fig. 1) consists of a chain or knife undercut mechanism. However, today, the chain is most often used because it is lighter and does not tear wood fibers on the cutting surface or cause cracks and fiberization in the cutting area. The saw is hydraulically driven. It has a more robust chain and higher performance than any other chain that can be operated by man. In addition, there are two or more bent delimbing knives that remove the branches around the perimeter of the tree. Their curvature depends on the quality of the delimbing as well as on the two rotating feeders (rollers) that work with the trunk in a horizontal position. The feeders can be either tracked or wheeled with different types of steel tips. Wheel studs on the sides allow the tree to be clamped with a harvester head. The wheels rotate to force the clenched tree through the delimbing knives

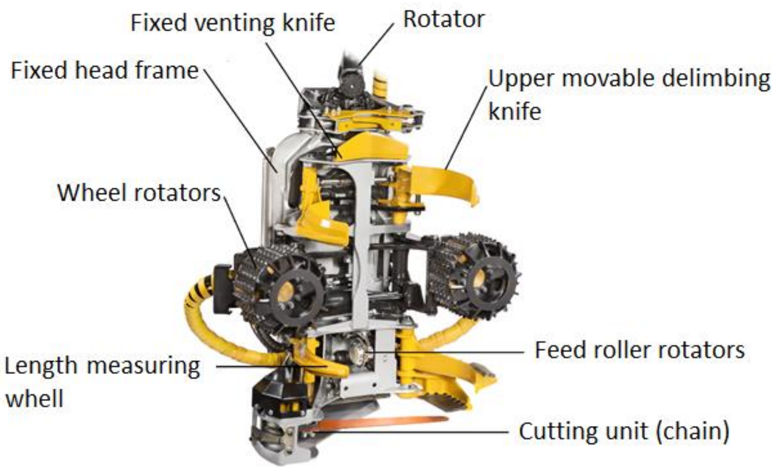

Fig. 1. Harvester head HW 60 (Kováč *et al.* 2017)

EXPERIMENTAL

Materials

One of the main components of wood processing in logging is delimbing the tree. This process is often made difficult by rugged and sloping terrain, so it is best to use mobile delimbing machines with multi-operational heads (Bodnár *et al*. 2016, Beňo *et al*. 2014).

Because the diameters of tree trunks in processing differ, delimbing knives may fail to properly encircle the tree trunk. In such cases there is an imperfect branching process, and residue from the delimbing or wood damage occurs. Such deficiencies can be eliminated by increasing the number of delimbing knives, where the angle of embedding, φ, of one knife is considered. For a straight-line shape if *d* (diameter) = 350 mm, *hk* (thickness of the cutting of the bark) = 100 mm then *hc* (branch balance height) = 8 mm. To eliminate these undesirable aspects, it is necessary to examine the individual parts of the machine.

After careful analysis and review of the literature, a design solution for a branching knife with a replaceable cutting edge was formed. The design of this knife was exceptional in that only the cutting edge of the knife needs to be replaced after wear. The technical solution was registered in July 2019 as a utility model at UPV SR (Industrial Property Office of the Slovak Republic). To evaluate whether a material is suitable for a sampling knife with a replaceable cutting edge, it was possible to experiment with flat knives. The results from the WinTestTM software were processed using STATISTICA 12 software (TIBCO Software Inc., Palo Alto, CA, USA). Stress analysis was designed in a computer analysis to design (CAD) system using the method Abaqus FEA (Abaqus finite element analysis software, Johnston, RI, USA). The Abaqus product is a software package for computer support of the newly modeled component that works using finite element analysis (Goubet *et al.* 2013).

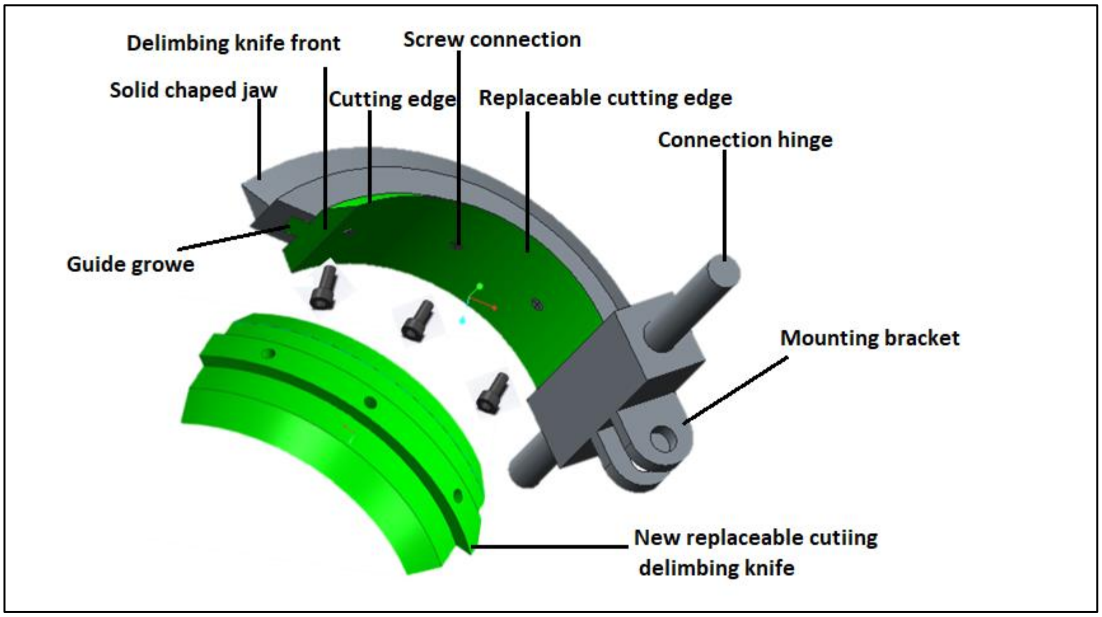

Fig. 2. Delimbing knife with replaceable cutting edge

Mathematical Geometry of Delimbing Knife

Equation 1 is the calculation of the cutting edge angle of the delimbing knife:

$$\cos\frac{\varphi}{2} = \frac{d-2.h_k}{d+2.h_k} = \frac{350-2.100}{350+2.8} = \frac{150}{366} = 0.4 = \varphi = 2.arcos0.4 = 84.55° \quad (1)$$

The number of knives at angle φ in radians is determined by the following relationship (Kováč *et al.* 2017):

$$z = \frac{2.\pi}{\varphi} = \frac{2.3.14}{84.55°} = 4.25 => z = 4ks \quad (2)$$

The length of the cutting edge of a straight knife can determined by the relationship:

$$l_0 = (d-2.h_c).\sin\frac{\varphi}{2} = (350-2.8).\sin\frac{84.55°}{2} = 224.71\ mm \quad (3)$$

To calculate the maximum cutting force when cutting branches:

$$F_c = \sigma_D.S_D = (\sin\delta + \mu_D.\cos\delta) = 10.28(\sin 36° + 0.50.\cos 36°) = 23.790\ kN \quad (4)$$

With some pairs of knives in the branch cutting mechanism, 60 to 70% of the total number of branches is cut by the first row of knives and the remaining 30 to 40% of the branches by the second row of knives.

The total cutting force $F_{\max}$ on the first row of knives will be:

$$F_{\max} = (0.7\ \div 0.75).i.F_{\max} \quad (5)$$

Cutting force $F_{2\max}$ on the second row of knives to clean a certain amount of branch residue with repeated trimming is calculated according to Eq. 6 (Krilek *et al.* 2018).

$$F_{2max} = (0{,}4 \div 0{,}3).\,i.\,F_{max} \tag{6}$$

RESULTS AND DISCUSION

The aim of the paper was to carry out a stress analysis of cutting forces on the design of a delimbing knife with a replaceable cutting edge. This delimbing knife was registered as an intellectual property and invention in July 2019 as a utility model UPV SR. The analysis was simulated on a single delimbing knife to which the material and other parameters were selected, on the basis of the maximum force at which the knives are loaded and at what points the strain deformations on the proposed knives are calculated (Bodnár *et al.* 2016; Kotsmíd *et al.* 2016). Stress analysis was designed in a CAD system using the method Abaqus FEA. The Abaqus product is a software package for computer support of the newly modeled component that works using finite element analysis (Goubet *et al.* 2013). Elements were created on the simulated models using hexahedron functions. For a replaceable cutting edge, a quadratic tetrahedron was used. Part of the simulation was to define friction contacts between the fixed part of the knife (stiffener) and the replaceable cutting edge at the end of the venting knife. The specified material density was ρ = 8200 kg.m^{-3}, young's modulus was 210 GPa, and Poisson's constant was 0.3. The simulated delimbing knife was loaded with the forces calculated from Eq. 4, where $F_{\max}$ = 23790 N.

For the removable cutting edge, STN 41 9 802 (SLAVIA STEEL s.r.o, Rimavská Sobota, Slovakia) was chosen, which was highly alloyed, resistant to shock, pressure, abrasion, and eliminated cracking (Ťavodová and Kalincová 2018). The use of the material is suitable for high-performance machine tools with a medium strength of up to 900 MPa for chip machining, such as milling cutters, turning and planing knives, and woodworking tools. It is resistant to degradation processes such as embrittlement and corrosion. After quenching in an oven at 1230 °C, it had a hardness value of 64 to 66 HRC (Rockwell hardness test) and was tempered 3 × 1 h between 560 and 580 °C (chemical breeding of steel slack). Using the Hypermesh software (Altair Engineering, Inc., Irvine, CA, USA), the networking of the model was launched, followed by a linear hexahedron that had eight nodes and a parabolic tetrahedron where each had 10 nodes. According to these parameters, the program can create a voltage analysis and evaluate the application of materials on the component

Measurements found that the minimum cutting force was 12.13 kN and the maximum cutting force was 23.79 kN. The average cutting force was 16.84 kN, which is further shown in Table 1. According to the formulas, the required cutting force of 16.48 kN was achieved. Therefore, it can be argued that the calculation according to the formulas was accurate as well as the proposed calculation methodology.

Table 1. Results Measurements from Program STATISTICA

No. of Measurments	Average	Min.	Max.	Lower Quartile	Upper Quartile	Standard Deviation	Variance
60	16844	12130	23790	15155	18135	2518.309	6341878

From Table 1 it is possible to read the values measured in the experiment, from which the measured values are the main value, the maximum and minimum cutting force detected during the measurements, and the upper and lower quartiles. The table shows that there was a big difference between maximum and minimum cutting force, because wood is a non-homogenous material.

A search of the literature on cutless research by Mikleš *et al.* indicate that the cutting force of the knife entering the woody plant initially increases linearly but then decreases to zero where the maximum cutting force corresponds to the knife penetration depth of 0.55 to 0.80 (half) diameter of the cut sample (Mikleš *et al.* 2004; Tuhársky *et al.* 2010). However, this is only true for circular wood samples. For the studied measurement, it was found that the maximum cutting force was achieved just before cutting the sample and it is shown in Fig. 3.

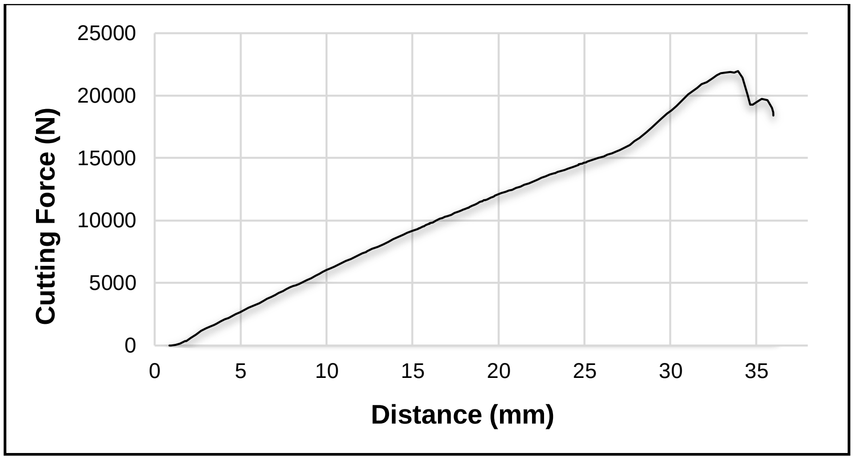

Fig. 3. Cutting force progress on the distance

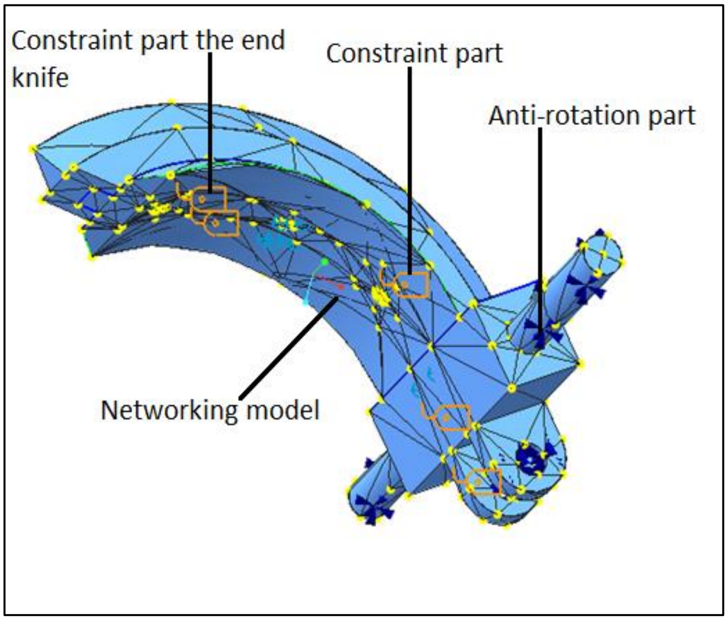

Fig. 4. Networking meshless model and setting the basic parameters in Hypermesh

Based on the evaluated numbers, Hypermesh software was used to simulate the stress FEM analysis from the application of the measured values. The forces required to load the test knife were read from the measurement graph. Using Hypermesh software, networking of the model was initiated, followed by a linear hexahedron that had 8 nodes and a parabolic tetrahedron, each with 10 nodes. They represent geometric shapes with a large number of nodes (vertices) that can connect individual points. According to the networking model, a mathematical calculation of the force and stress deformations of the delimbing knife was performed.

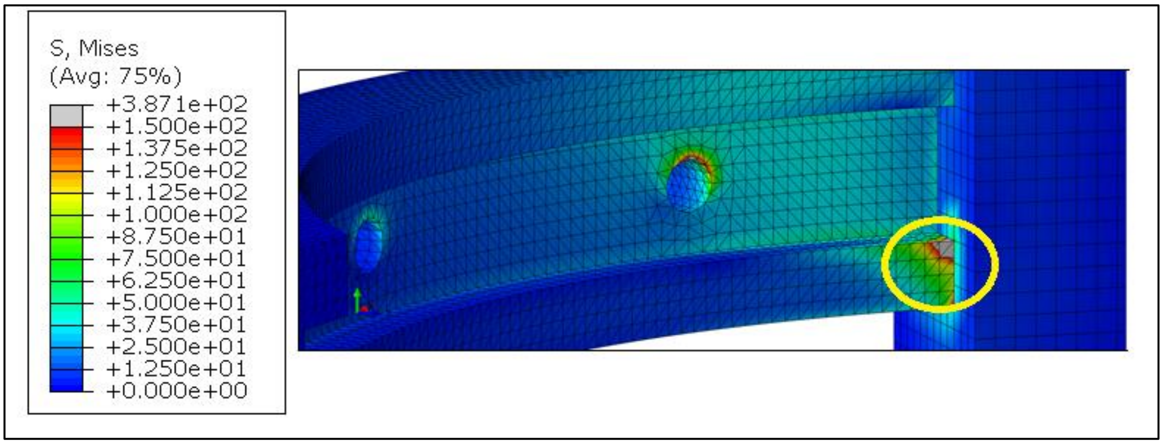

Fig. 5. Stress waveform according to stength method analysis von Mises

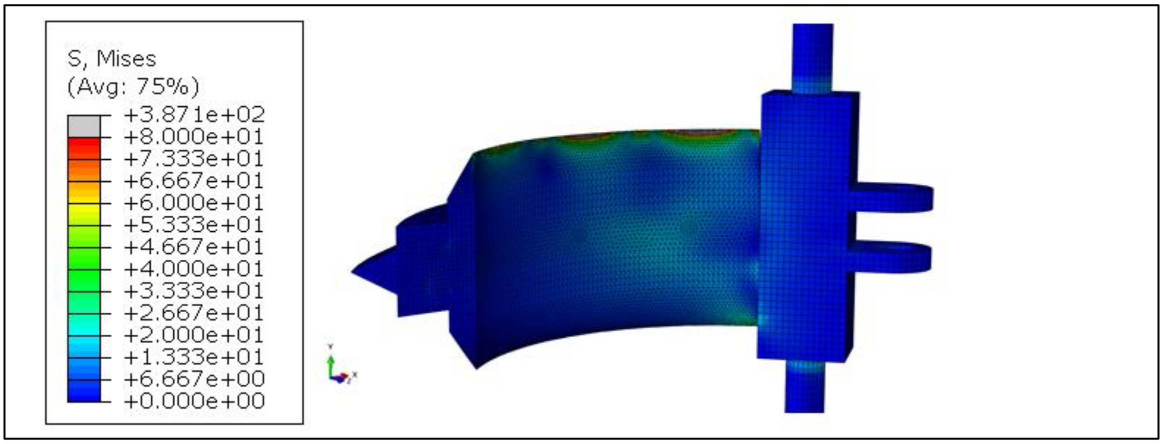

Fig. 6. Deformation of replaceable cutting edge

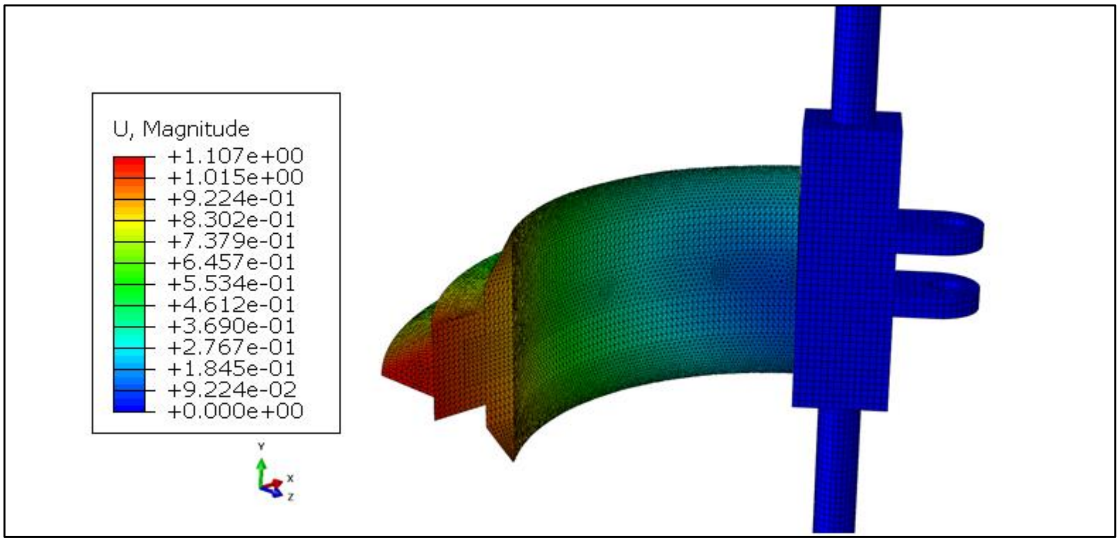

Fig. 7. Stress delimbing knife

Stress analysis according to von Mises stength method is the ouput above and displays the voltage, which occurs after the simulation was performed in individual points at a max of 387 MPa in places where damage could occur. Due to the storage of the weld (rounding) at these points, the resulting voltage will certainly be smaller.

U, Magnitude

U is the displacement where magnitude displays the combined magnitude of both the real and imaginary portions of the result value. The output of the voltage analysis showed the total deformation of the venting knife, where the calculation was made using vectors created from all axes. At the end of the knife there was a deflection of 1.1 mm, which determined that the deflection did not affect the functionality of the knife.

The calculated stress and strain analyses are shown in Figs. 6 and 7. Figure 6 shows a maximum stress of +3.871e +02 Pa. Deformation stress in basic form is given in Pascal units. The stress analysis value is converted to MPa in the resulting calculation. The value of this analysis would certainly change with respect to the type of bonding (*e.g.*, inserting the weld). The stress analysis indicated that the material proposed by the authors is suitable. The maximum deformation is shown in Fig. 5, where the replaceable blade was replaced with a force according to Eq. 4. Figure 6 shows the maximum stress at the knife radius, where the resulting bending value is 1.1 mm, which is an indication that does not limit the function of the delimbing knife. The load value was 387 MPa, which corresponded to the properties of high speed cutting steel STN 41 9802.

CONCLUSIONS

1. The results from the Statistica 12 software evaluated the maximum wood processing force of 23.79 kN.
2. Outputs from the stress and strain analysis created by Abaqus software confirmed the appropriate design of the material for the production of a replaceable cutting edge knife. Defined input variables are based on older studies and harvester parameters.
3. The stress analysis outputs display the maximum stress 387 MPa, and this value of the stress analysis would certainly change with respect to the type of bond, for example, inserting a weld or other way of fastening individual components of a branch knife.
4. The maximum deformation is shown at the output of the stress analysis, where the cutting blade loaded with a load force of 23.79 kN. Notably, this value does not violate the structure and properties of the knife, which is suitable for the subsequent production of this type of knife and its use in practice.
5. Damage of the delimbing knife with replaceable cutting edge occurred under stress of 387 MPa, which confirms a suitable choice of material with the properties of high speed steel STN 41 9802.

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