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## A dynamic measurement of a disc chipper cutting forces

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Abstract: Nowadays wood chips produced from raw material of inferior quality are mainly used to feed domestic and industrial boilers. For this use, a good chip size distribution and low manufacturing energy consumption are required. Cutting forces are still inaccurately measured during the wood chipping process, which implies the use of oversized chippers' motors. A test bench for chipping wood under reasonably realistic conditions of industrial production is improved by adding an indirect force measurement system with high bandwidth of 3 KHz. The dynamic experimentations give the data needed to compute the curve presenting the vertical component of the cutting force, which is composed of three sections; the first one presents the values of the impact force; the second one is relatively straight and it refers to shear stress in wood; the third section corresponds to the period between two crosscuts.

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Subject: **SUBMISSION OF A MANUSCRIPT FOR EVALUATION**

Dear Editor

I am enclosing herewith a manuscript entitled “**A dynamic measurement of a disc chipper cutting forces**” for publication in “Biomass & Bioenergy” for possible evaluation.

This study follows the one entitled “Experimental study about the effects of disc chipper settings on the distribution of wood chip size”, which was already published in “Biomass & Bioenergy”. The aim of this study is to produce a good chip size distribution consuming as low as possible energy in the production of these chips.

The paper fits the journal themes: “Biomass sources, energy crop production processes, wastes from forest, processing industries”. The measurement of cutting forces has important and extensive applications in the wood chipping operations, e.g. optimizing the cutting parameters, helping to study chip formation and to estimate the chipping cost.

The goal of our project is to provide solid knowledge in the wood chipping process; this paper represents our second results that will help to achieve this objective. Due to the lack of studies on the cutting forces during the chipping process, wood chipper motors are oversized, which increases the wood chips production cost. Chipper manufacturers and wood chip producer would be interested, so they will be able to meet the need of producing high quality chips with minimum level of energy consumption. The strong point of our analysis is to propose for the first time accurate prediction values of the cutting forces in the wood chipping field. We strongly believe the contribution of this study warrants its publication in the “Biomass & Bioenergy” Journal.

Finally, this paper is our original unpublished work and it has not been submitted to any other journal for reviews.

Sincerely,

Sébastien AUCHET

Journal Biomass & Bioenergy

### Highlights

- A cutting force measuring device is implemented on our real size chipping test bench.
- The vertical chipping force  $F_y$  is accurately measured using FRF method compensation.
- $F_y$  has three parts: an impact, then a constant value ended by a decrease to zero.
- Increasing the cutting speed led to decrease  $F_y$  if the other cutting parameters are constant.

# 1 A dynamic measurement of a disc chipper cutting 2 forces

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## 9 Abstract

10 Nowadays wood chips produced from raw material of inferior quality are mainly used to feed  
11 domestic and industrial boilers. For this use, a good chip size distribution and low  
12 manufacturing energy consumption are required. Cutting forces are still inaccurately  
13 measured during the wood chipping process, which implies the use of oversized chippers'  
14 motors. A test bench for chipping wood under reasonably realistic conditions of industrial  
15 production is improved by adding an indirect force measurement system with high bandwidth  
16 of 3 KHz. The dynamic experimentations give the data needed to compute the curve  
17 presenting the vertical component of the cutting force, which is composed of three sections;  
18 the first one presents the values of the impact force; the second one is relatively straight and it  
19 refers to shear stress in wood; the third section corresponds to the period between two  
20 crosscuts.

21 **Key words:** cutting forces, wood, chipping, disc.

## 22 1. Introduction

23 The measurement of cutting forces has important and extensive applications in the wood  
24 chipping operations such as supervising of the tool wear evolution, optimizing the cutting  
25 parameters, helping to study chip formation and estimating the chipping cost. Even though the  
26 disc chipper was invented in 1889 under the Wigger brand, there is still lack of studies on the

27 cutting forces during the chipping process. As no accurate prediction laws of cutting forces  
28 for wood chipping exist, wood chipper motors are oversized, increasing the wood chips  
29 production cost.

30 In our previous paper [1], we studied the effects of four chipping parameters: feed per tooth,  
31 rake angle, sharpness angle and cutting speed, on the distribution of the wood chip size.

32 In Fig 1, the traditional cutting angles are represented: the cutting angle which is also called  
33 the rake angle ( $\gamma$ ), the sharpness angle ( $\beta$ ), the clearance angle ( $\alpha$ ). The sum of these three  
34 angles is always 90. Using these angles make it possible to know the angles between the knife  
35 faces and the disc. We have added a fourth angle (Fig 1(2)), which we have called the real  
36 cutting angle ( $\gamma_r$ ). It is the angle between the cutting face and the grain direction. This angle  
37 has an important effect on both chip formation and cutting forces [2].

38 <Fig 1>

39 Hartler[3] studied the chipping process at high cutting speed (5, 10, 15 and 20 m/s) and  
40 proposed an idealized diagram for the vertical reaction force (Fig 2), which is recorded from  
41 the anvil during the chipping process. In this study, the force rises rapidly and reaches a  
42 maximum value called “impulsive force” when the knife hits the wooden rod. Then, the force  
43 drops down to a constant value called “chipping force” before becoming zero when the knife  
44 leaves the wood.

45 <Fig 2>

46 Hartler concludes that the sharpness angle ( $\beta$ ) only affects the impulsive force when the knife  
47 hits the sample, and that the impulsive and cutting forces increase when increasing the cutting  
48 speed and the dry content of the wood. He also underlines the difficulty of making reliable  
49 measurement of cutting forces during high-speed chipping.

50 The results of Uhmeier [4], who studied the wood chipping at low cutting speed (up to 0.08  
51 m/s), show that the bigger the clearance angle ( $\alpha$ ) and the chip length, the greater the cutting  
52 force's components. Whereas Hellström [5] disagrees with Uhmeier about the influence of  
53 the chip length, she didn't find any influence of it on the cutting force for similar cutting  
54 speed. But Uhmeier and Hellström [6,7] agree that an increase of the friction between the  
55 knife and the wood leads to rise the cutting force. At these cutting speeds, there is only the  
56 "chipping force" part and not the impulsive one, which in it the energy consumption is the  
57 most important.

58 Recently, Hellström [8] built up a laboratory wood chipper able to operate under conditions  
59 similar to the real ones, the cutting speed can reach 50 m/s. The chipper uses one knife  
60 mounted on a holder instrumented by four 3-components dynamometers. Even if a simple two  
61 degrees of freedom model is used to take into account inertial effects, the measured cutting  
62 force diagram is very different from that obtained in Hartler's study. The dynamic behavior of  
63 the system composed of the disc, the knife and its holder could be modified by the use of the  
64 dynamometers, which cause a big effect on the chipping process.

65 To summarize, in spite of the importance of measuring the cutting forces during the wood  
66 chipping process, there wasn't yet any reliable measurements of the chipping force. Most of  
67 the existing measurements attempts were done under unrealistic chipping conditions with low  
68 cutting speed or specific chippers.

## 69 **2. Materials and methods**

### 70 **2.1 Test bench**

71 Using the chipping test bench we presented in our earlier paper [1], the effects of many  
72 parameters can be tested under real conditions. This test bench is constituted of two  
73 independent units (Fig 3): a disc chipper and a feeding mechanism.



74 The disc weighs 182 kg and has a diameter of 950 mm. A variable speed driver allows us to  
75 modulate the disc's rotation speed from 1 to 1000 rpm corresponding to a variable cutting  
76 speed from 0 to 32 m/s at the middle of the knives. It is possible to use either two or four  
77 knives. The chipper is powered by 21 Kw asynchronous motor. The feeding speed which is  
78 controlled by a second variable speed driver and a gearbox can be varied from 0 to 25 m/min.

79 <Fig 3>

80 In our cutting configuration, the vertical component of the cutting force ( $F_y$ ) is considerably  
81 more important than the two others (Fig 4). Therefore, we decided to measure this component  
82 in order to test our cutting force measurement method.

83 <Fig 4>

## 84 **2.2 Measurement of anvil longitudinal strain during chipping**

85 In order to be able to measure the cutting force, we built up an indirect measurement system  
86 which consisted of the anvil of the chipper (Fig 5) and two surface strain sensors (type  
87 Kistler-9232A), screwed to the middle of the anvil underside.

88 <Fig 5>

89 The anvil is made of steel S235JR and has a thickness of 22 mm above the strain sensors. This  
90 thickness allows at the same time to measure strains from 50 to 75 % of the full scale of the  
91 sensors (from -300 to 300  $\mu\epsilon$ ), and to damp anvil vibrations between two consecutive cuts.  
92 During the chipping process, the sensors measure anvil's longitudinal strains caused by the  
93 vertical component of the cutting force (Fig 6).

94 <Fig 6>

## 95 **2.3 Functions linking vertical chipping force to anvil's longitudinal strain**

96 The Frequency Response Function Method (Auchet [9] Ricardo [10]), also called FRF  
 97 method, is used to calculate the force's vertical component from anvil's longitudinal strain.  
 98 This approach is based on the construction of a complex correction function taking into  
 99 account the dynamic behavior of the anvil. This method allows measuring the chipping force  
 100 for a large frequency domain exceeding 3 KHz, without modifying the chipper dynamic  
 101 behavior. When the chipper is not running, the complex equation of Transmissibility between  
 102 chipping forces and anvil longitudinal strain is obtained by using an impact hammer in order  
 103 to apply located excitations on the anvil. Fig 7 shows three points where the anvil is hit by the  
 104 hammer. At each impact, three signals are recorded simultaneously: an impact force ( $E_j(t)$  in  
 105 N) and two longitudinal strains ( $S_1(t)$  and  $S_2(t)$  in  $\mu\epsilon$ ) in response to the hammer hit.

106 <Fig 7>

107 The Fast Fourier transforms (FFT) is then applied to excitation and response signals  $E_j(t)$ ,  
 108  $S_1(t)$  and  $S_2(t)$  in order to obtain their frequency domain spectra, i.e.  $E(j\omega)$ ,  $S_1(j\omega)$  and  
 109  $S_2(j\omega)$ .

110 As the anvil is supposed to have a linear behavior, the modal analysis is applied at point 1,  
 111 which gives:

112 
$$\text{With } \text{---} \quad (1)$$

113 Where  $i$  and  $j$  indicate the response and the excitation degrees of freedom respectively. In our  
 114 case,  $i$  points to one of the two output signals which are emitted by the strain sensors, and  $j$   
 115 represents one of the three excitation spots (Fig 7).

116 The Frequency Response Functions (FRF), i.e.  $H_{ij}(j\omega)$  are obtained by measuring the anvil's  
 117 longitudinal deformations ( $S_1$  and  $S_2$  in Volts), which are recorded when impulses are

118 applied to the excitation points in the direction  $Y$  ( $E_j$  in  $N$ ). These FRF are complex functions  
119 which can be compared to frequency dependant sensitivity functions. (Fig 8)

120 <Fig 8>

#### 121 **2.4 Determination of the vertical cutting force ( $F_Y$ )**

122 During the chipping process, the signals emitted by the strain sensors are recorded and then  
123 corrected by using the FRFs functions. Equation 1 must be inversed in order to obtain an  
124 expression of the chipping forces from the anvil strains and the FRFs functions;

125 
$$\text{—————} \quad (2)$$

126 Where  $H_{ij}^*$  is the conjugate term of the complex function  $H_{ij}$

127 The cutting force  $E_I(t)$  (or  $F_y(t)$ ) is obtained by applying an inverse FFT to the function  
128  $E_I(j\omega)$ .

#### 129 **2.5 Samples characteristics and cutting conditions**

130 Spruce (*processus spinosus*) and fir (*Abies alba*) were chosen as representatives of softwood  
131 in the French forest. The samples have an average diameter of 90-115 mm, taper from 1mm/m  
132 to 10 mm/m and length of 1000 mm. All logs are green, the moisture content ranges from  
133 44% to 55% on wet base.

134 The feeding direction was: the horizontal feeding angle ( $\rho$ ) =  $90^\circ$ , the vertical feeding angle  
135 ( $\varepsilon$ ) =  $90^\circ$ . The number of knives (two) remained constant during the experiments. The tested  
136 parameters are the feed per tooth ( $f_z$ ), the cutting angle ( $\gamma = \gamma_r$ ), the sharpness angle ( $\beta$ ) and the  
137 cutting speed ( $V_c$ ), which is calculated at the middle of the knife (Table 1).

138 <Table 1>

139 The positioning coordinate of the anvil center ( $K$ ) remained constant during our experiments  
140 in the reference ( $OXY$ ), the point  $O$  is the center of the disc (Fig 9). This is why the cutting  
141 forces located in the plane ( $OXY$ ) always move along the same path. Hence, the samples tend  
142 to move towards the axis  $OY$  when they are not held in place by the feeding wheel.

143 <Fig 9>

## 144 **2.6 Force curve signal processing**

145 After computing the vertical components of the cutting forces by using the Frequency  
146 Response Function (FRF) method, accurate steps were followed to process the force curves  
147 signals and to extract representative results.

148 The width of cut is the distance across the face of the log contacted by the knife (Fig 9). It  
149 varies from zero as the knife first comes in contact with the log, to the diameter of the log  
150 when the knife is halfway through the cut, and decreases to zero again as the knife leaves the  
151 log. The variation of the width of cut ( $b$ ) from the log diameter and the knife speed obtained  
152 by a simple geometrical program fits very well the chipping force measurements (Fig 10).

153 <Fig 10>

154 Vertical chipping forces curves are divided by their width of cut to obtain vertical cutting  
155 forces per cm of the cutting width.

156 Then, in order to increase the accuracy of experimental chipping force measurement, the peak  
157 sections of the force graphs are considered as consecutives cuts of one chipper knife. Each  
158 peak section corresponds to a half disc turn, because the disc has two knives. The chipping  
159 force diagram presented in Fig 11 is the average of isolated knife cuts after elimination of the  
160 aberrant ones.

161 <Fig 11>

162 On each point of the average curve the standard deviation ( $\sigma$ ) is added. The numbers of  
163 averaged and measured cuts are shown on the diagram. During our experiments, at least 150  
164 cuts are averaged representing more than 70% of measured data.

### 165 **3. Results and discussion**

#### 166 **3.1 Shape of the force curve in wood chipping**

167 The Fig 12 presents the geometry and the general form of the force curve ( $F_y$ ). Three sections  
168 can be distinguished in this curve. The first one corresponds to the dynamic impact resulting  
169 from the high speed penetration of the knife in the wooden log. The second represents the  
170 chipping force, while the third section shows the decrease of the force when the knife is about  
171 to finish the cutting action. Ideally, the force value should be equal to zero when the knife has  
172 no contact with the log, but a little noise is observed in the measurements.

173 <Fig 12>

174 Our results are similar to Hartler's idealized diagram [3]

175 The initial impact of the knife allows it to penetrate deeply in the log. This part of the cutting  
176 action has no definition in the traditional laws of the wood machining, and the force value  
177 could be 25 to 50 percent greater than its value during the chipping part. In the second part of  
178 the cutting action, wood fibers are destroyed under the shear stress. The time of this part is  
179 very short since we use samples with diameters less than 15 cm. After the second part, the  
180 fibers will be pulled off by the knife during its exiting from the wood. Just to give an idea  
181 about the dynamics of the cutting action, a knife moving with a speed of 26 m/s can cross a 10  
182 cm diameter of wood in 5 ms.

183 The Fig 13 shows the tendency curve of the first section of the force graph, it is a second  
184 order polynomial curve. The second section can be represented by one medium value, which  
185 is the value of the force that destroys the wood fibers under the shear stress.

186 <Fig 13>

### 187 **3.2 Results of the repeatability test**

188 In order to quantify the repeatability of our measuring method, the chipping test was repeated  
189 five times. The samples were made from spruce with a moisture content  $50\% \pm 2\%$  wet basis.  
190 The logs have a length of 1000 mm, an average diameter between 85 and 115 mm, and a taper  
191 between 6mm/m and 12 mm/m.

192 The other cutting conditions are: a cutting speed ( $V_c$ ) of 26 m/s, a feed per tooth ( $f_z$ ) of 8 m/s  
193 and cutting angles ( $\gamma_r = 50^\circ$ ,  $\beta = 34^\circ$ ,  $\alpha = 6^\circ$ ).

194 The Fig 14 shows one of the five graphs of  $F_y$ . These graphs took into account the majority of  
195 isolated knife cuts after having eliminated aberrant ones.

196 <Fig14>

197 Table 2 **Error! Reference source not found.** highlights the different values extracted from  
198 the five force graphs. Three coefficients present the first section “Dynamic impact” with an  
199 average precision of 15%. The average precision of the second section values “chipping  
200 force” is 20%.

201 <Table 2>

### 202 **3.3 Effects of some factors on the cutting force**

203 The first fifty exploratory tests were carried out in order to disclose the tendency of the effects  
204 of the feed per tooth ( $f_z$ ), the cutting speed ( $V_c$ ), the cutting angle ( $\gamma_r$ ) and the sharpness angle  
205 ( $\beta$ ) on the chipping force. The chosen values of these parameters are showed in the Table 1 of  
206 the paragraph 2.4.

207 Due to interactions between the factors effects, accurate study results can be achieved by  
208 analyzing different factors simultaneously. At first, nine cutting configurations were tested by

209 jamming the cutting angles ( $\gamma_r = 50^\circ$ ,  $\beta = 34^\circ$ ,  $\alpha = 11^\circ$ ) and varying  $f_z$  and  $V_c$ . In the majority  
210 of tests, only the first section of the cutting force curve "dynamic impact" appeared, whereas  
211 the second section "chipping force" appeared only in the third of the resulted curves. In fact,  
212 when a high value of the cutting speed (32.4 m/s) is chosen or when the diameter of the  
213 chipped logs is too small (under 90 mm), the penetration of the knife in the log is deeper  
214 during the impact. Consequently, the second part of the cutting action is very quick and there  
215 is not enough time to appear.

216 Similar results were obtained when the sharpness angle ( $\beta$ ) and  $V_c$  were varied simultaneously.  
217 In these experiments, two different values are chosen for  $\beta$  and three were taken for  $V_c$  (Table  
218 1), the values of the other parameters were:  $f_z = 8$  mm,  $\gamma_r = 50^\circ$ . The graph of cutting force  
219 obtained with a  $34^\circ$  angle has two parts, whereas only one part appeared with  $25^\circ$  sharpness  
220 angle. We believe that these results are still caused by the small diameter of the used samples.

221 The real cutting angle ( $\gamma_r$ ) and the speed ( $V_c$ ) were also varied together to disclose the  
222 tendency of their effects. Each of them had three values, while the feed per tooth and the  
223 sharpness angle had constant ones ( $f_z = 8$  mm,  $\beta = 34^\circ$ ). The results are shown in Fig 15. Two  
224 clear tendencies are visible on the figure: the cutting force ( $F_y$ ) with the angle  $55^\circ$  is greater  
225 than its values with the other angles ( $45^\circ$ ,  $50^\circ$ ), and increasing the cutting speed led to  
226 decrease  $F_y$  if the other cutting parameters remained constant.

227 <Fig 15>

## 228 **4. Conclusion**

229 Cutting force measuring device is successfully implemented on our chipping test bench. The  
230 graph of the force  $F_y$  is composed of three sections. The first one which represents high speed  
231 penetration of the knife in the log is highly affected by the inertia of the rotated disc. The  
232 second section illustrates the force which leads the wood fibers to be destroyed under the

233 shear strength. The third section shows the decreasing of the force when the knife is about to  
234 finish the cutting action. Exploratory tests showed the tendency of the effects of some factors  
235 on the force. This study is an important step in our works to understand the chipping operation  
236 process in order to produce the suitable chip size with minimum of energy. The obtained data  
237 of the  $F_y$  graphs will be helpful to construct our model of the chipping process cutting laws.

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**Table 1**

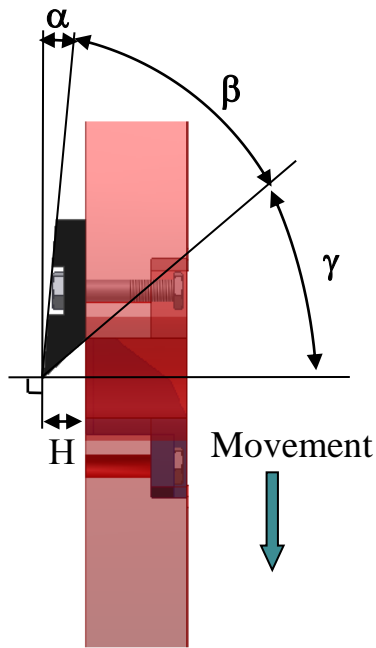
<b>fz (mm)</b>	<b><math>\gamma</math> (°)</b>	<b>Vc (m/s)</b>	<b><math>\beta</math> (°)</b>
2	45	19	25
4	50	26	34
8	55	32.4	

Table 1- Values of the tested parameters

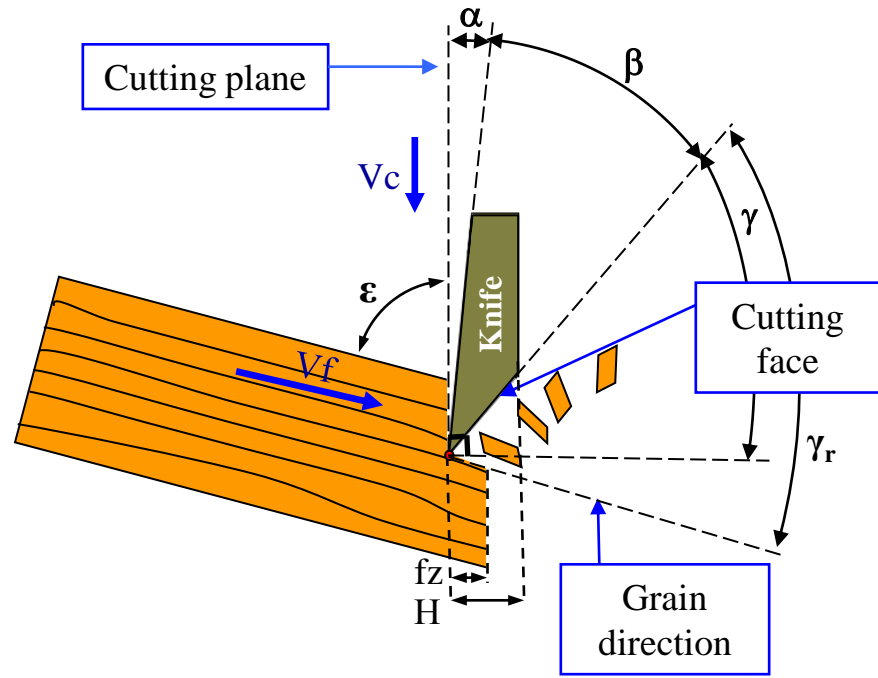
<b>Test</b>	% of peak sections taken into account	Coefficients of second order polynomial curve representing the impact		
		<b>X<sup>2</sup></b>	<b>X</b>	<b>cst</b>
<b>1</b>	(276/388) : 71%	-2.0E+08	1.0E+06	-1.2E+03
<b>2</b>	(214/243) : 88%	-7.0E+07	4.6E+05	-1.4E+02
<b>3</b>	(138/168) : 82%	-1.0E+08	9.1E+05	-6.9E+02
<b>4</b>	(147/160) : 92%	-2.0E+08	1.0E+06	-1.2E+03
<b>5</b>	(160/172) : 93%	-2.0E+08	1.0E+06	-1.0E+03

Table 2- Data of the Fy graphs which are resulted from the repea

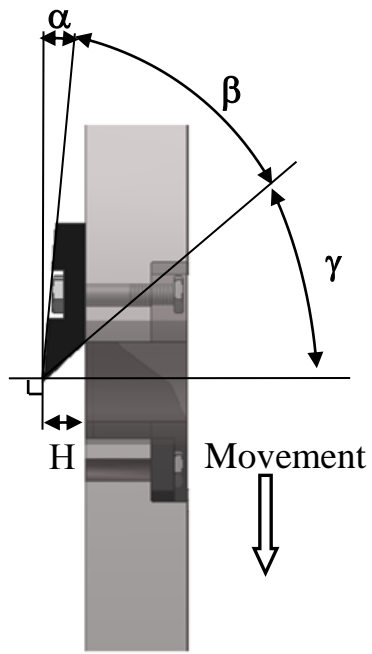
Figure 1



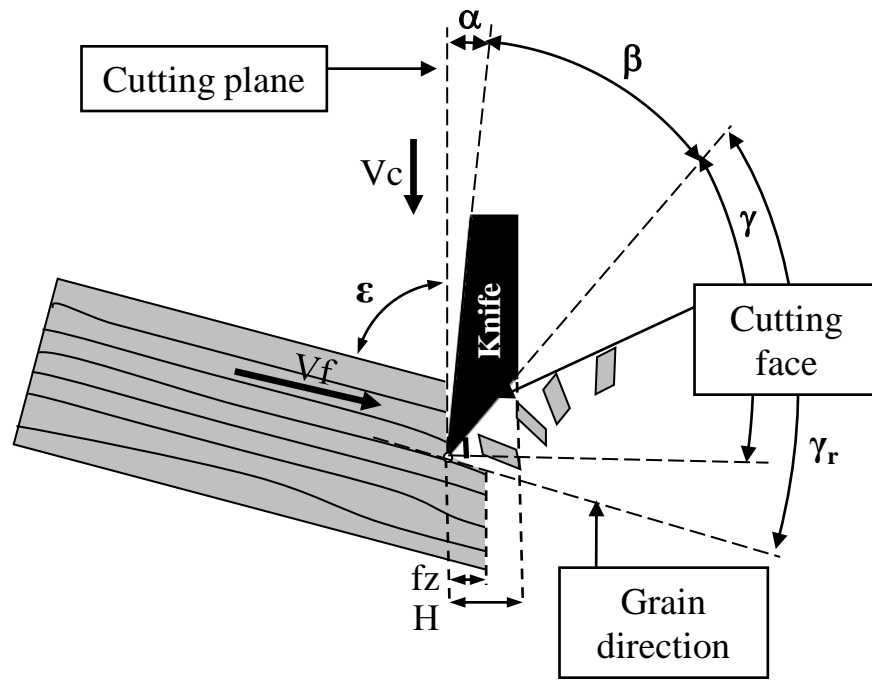
(1)



(2)



(1)



(2)

Figure 2

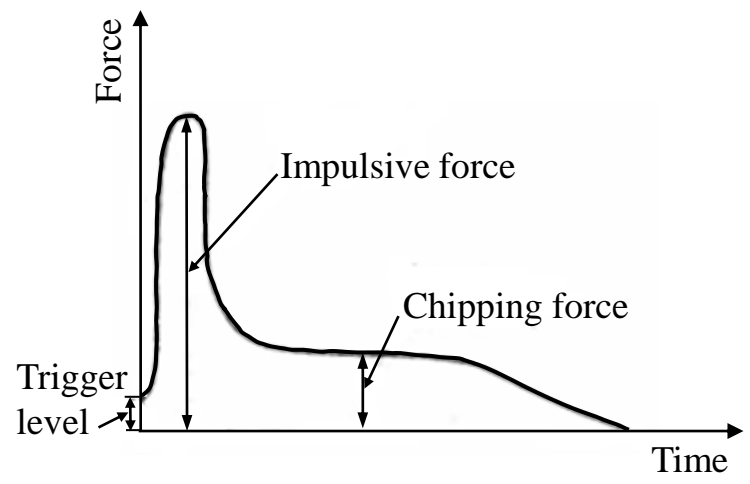
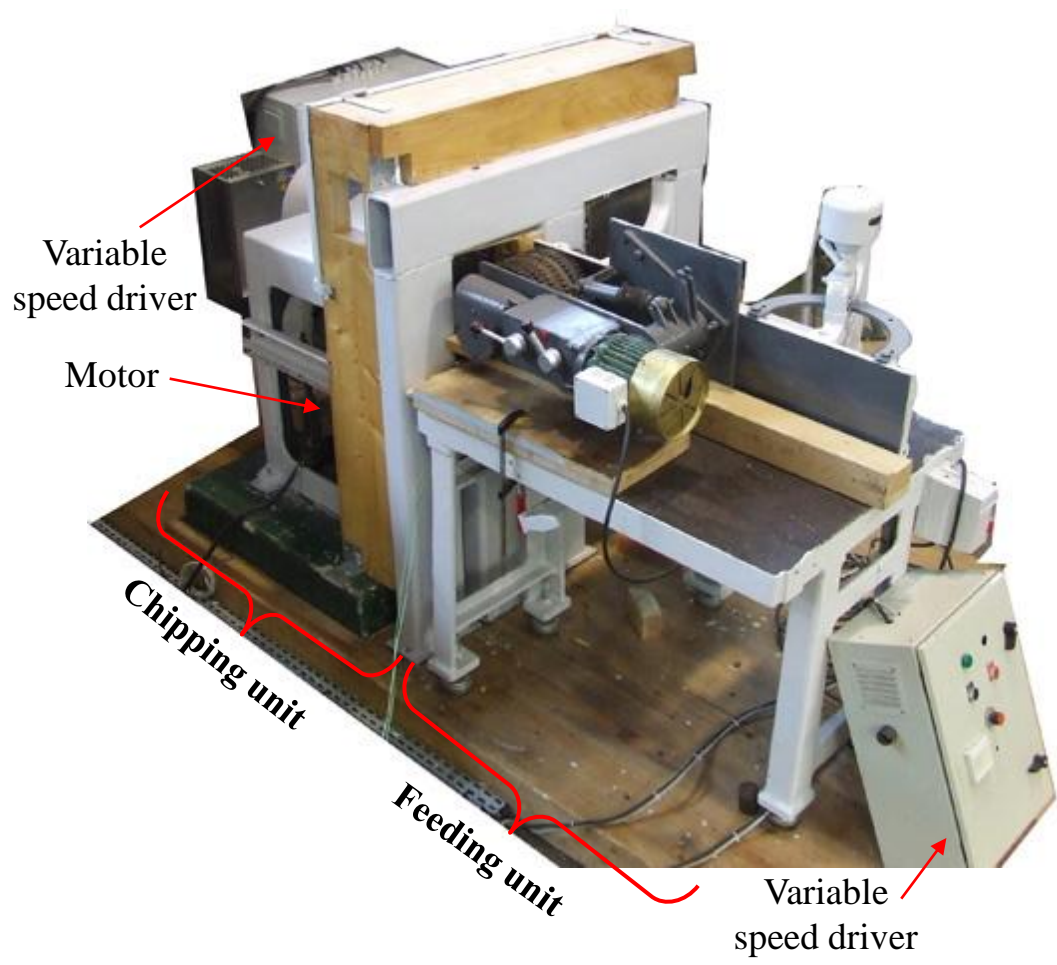
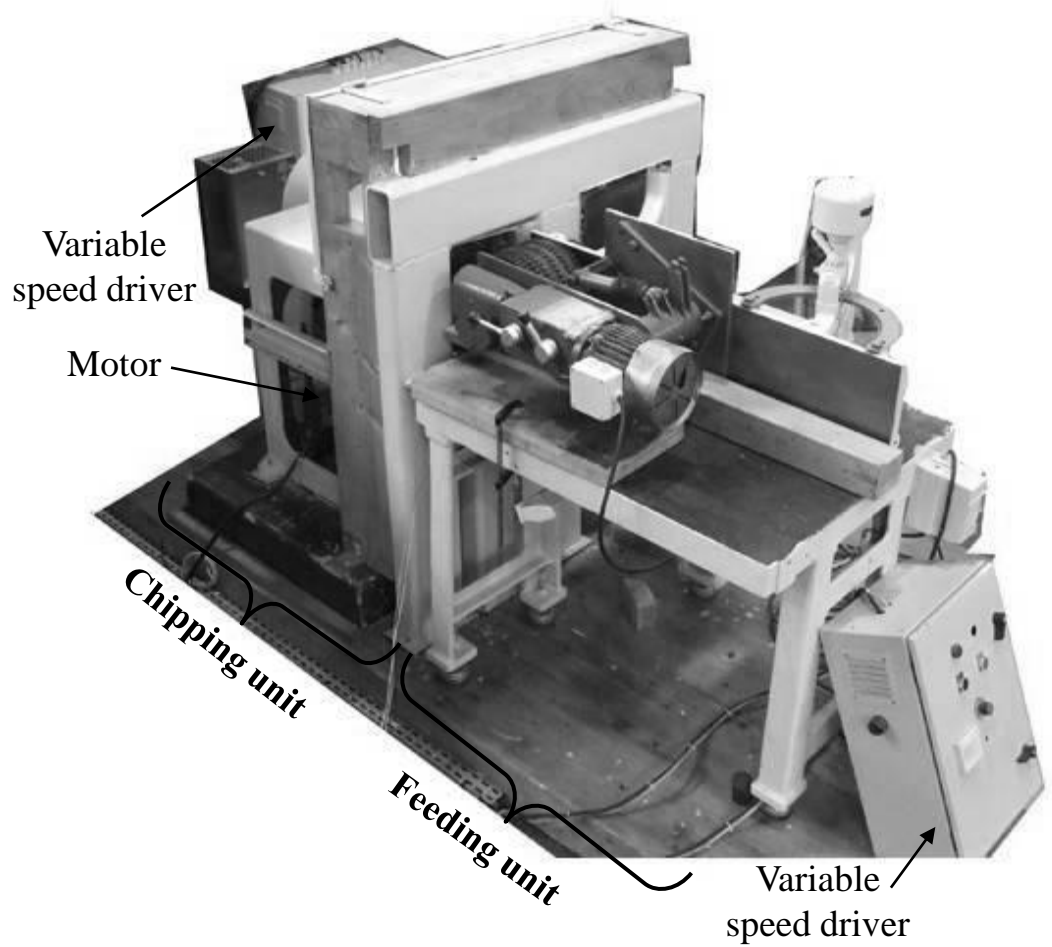


Figure 3





Variable speed driver

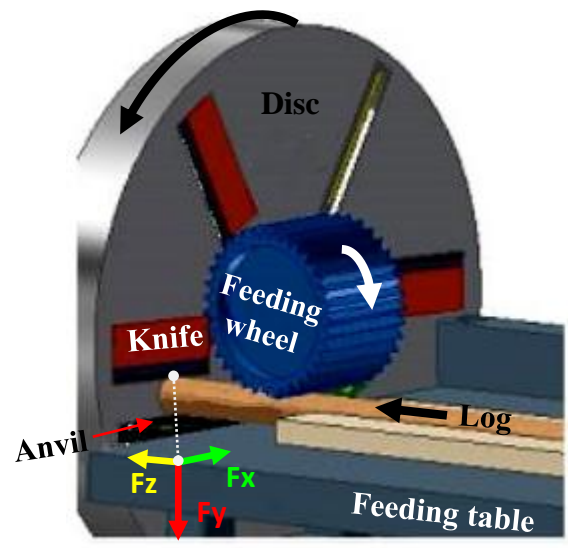
Motor

Chipping unit

Feeding unit

Variable speed driver

Figure 4





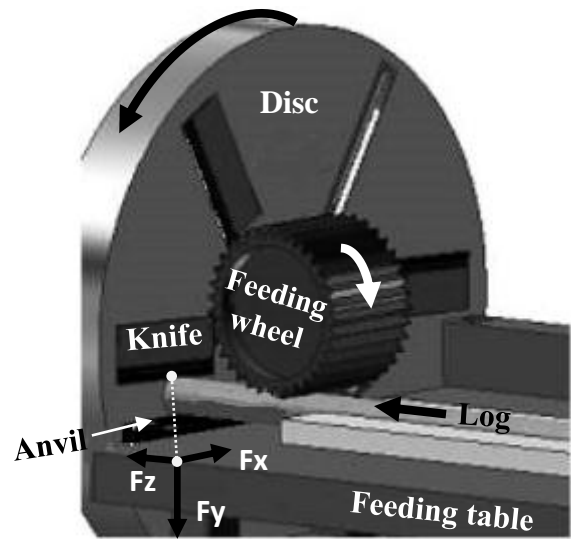
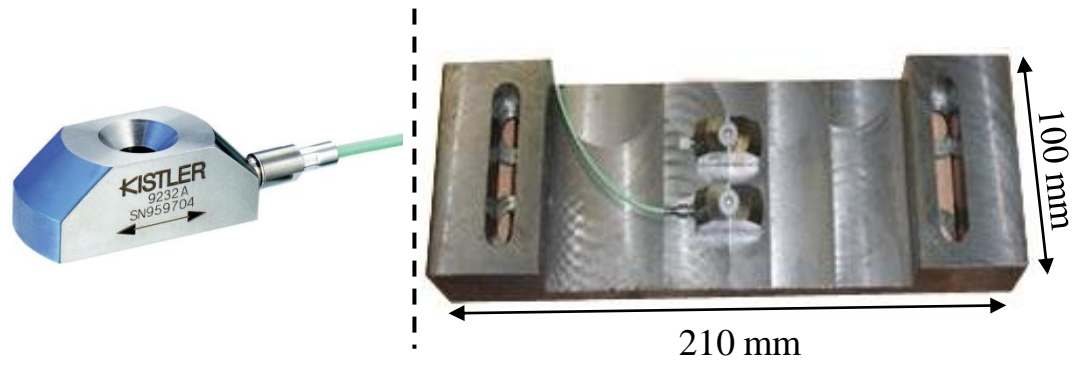


Figure 5



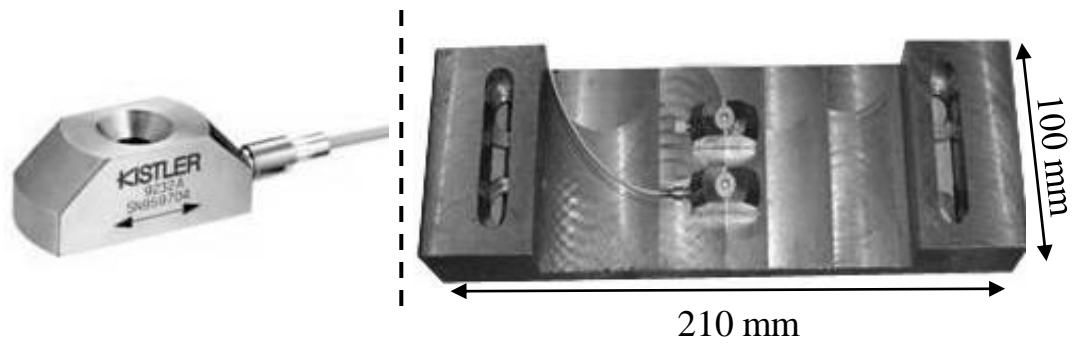


Figure 6

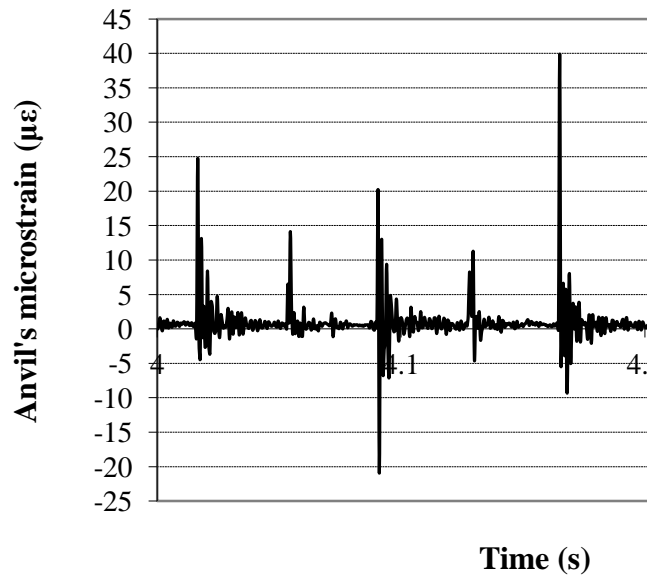
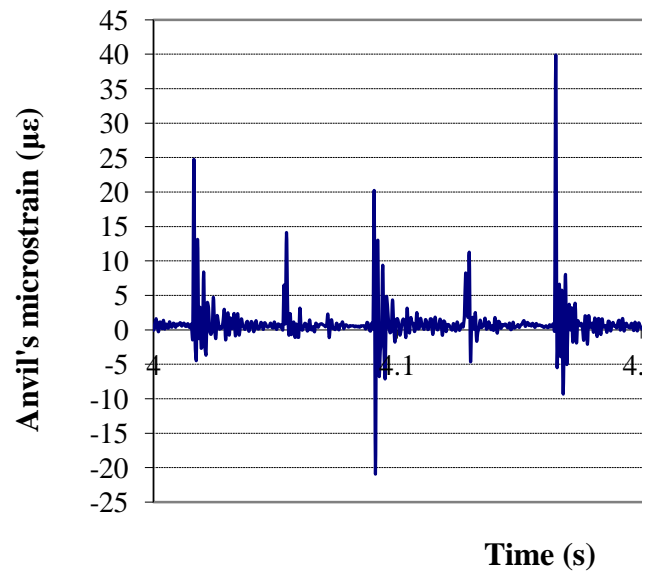
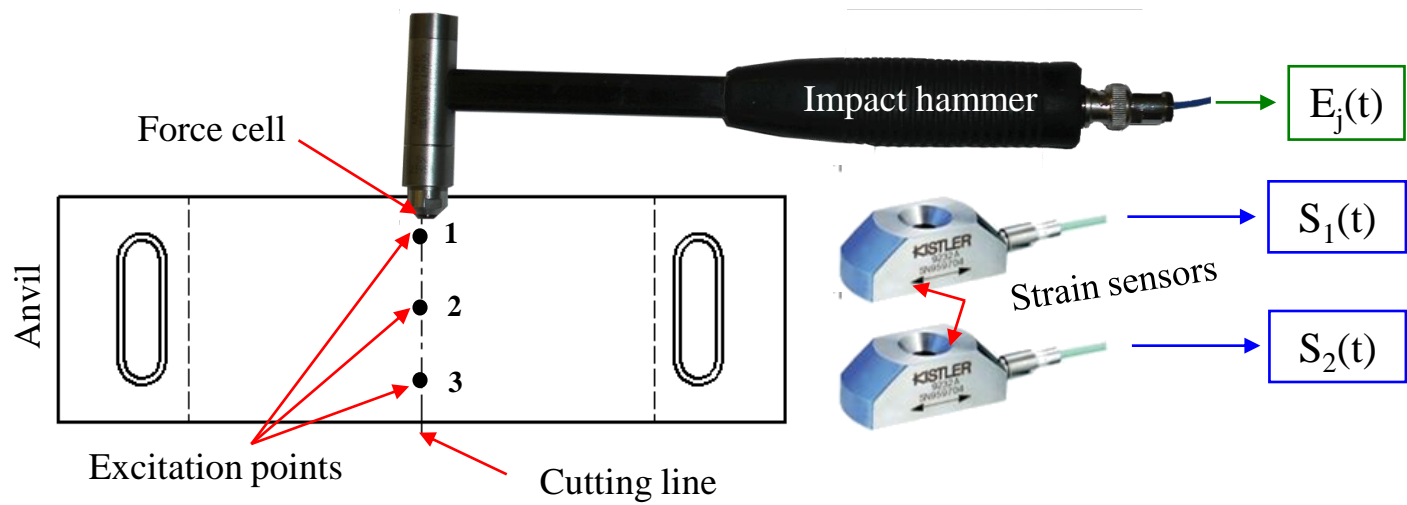


Figure 7



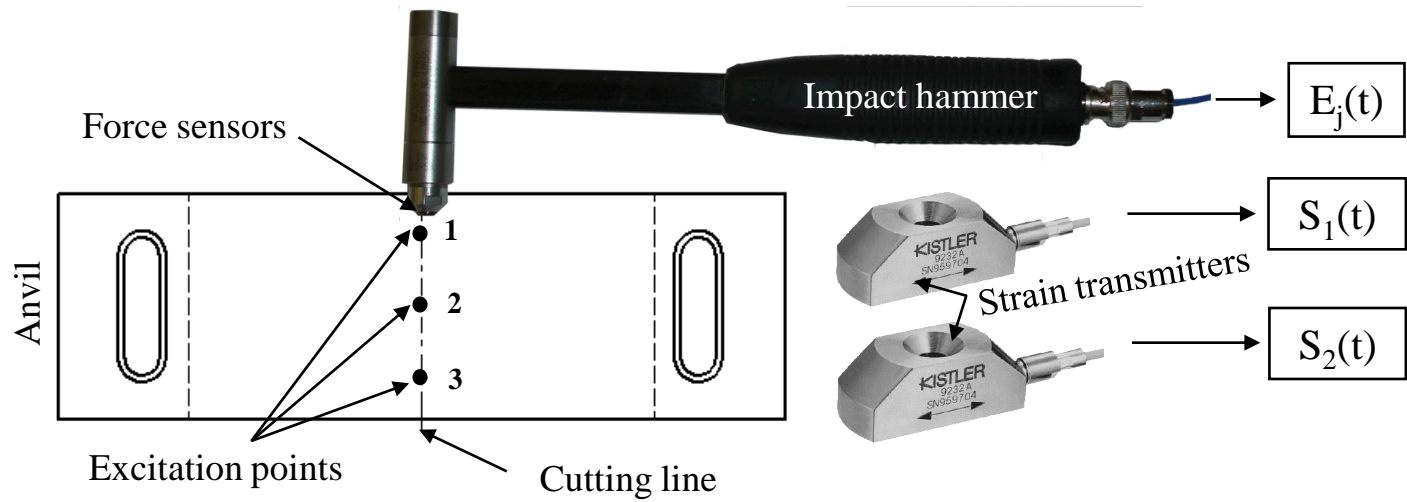


Figure 8

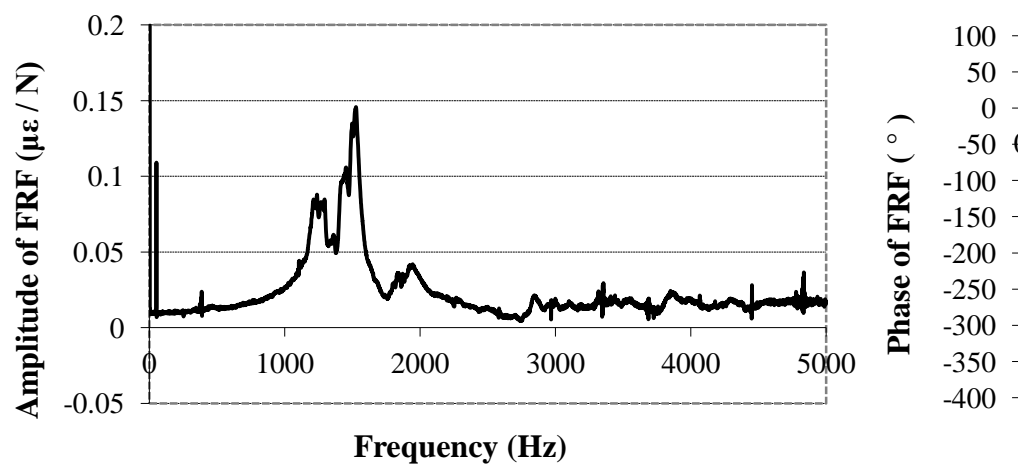
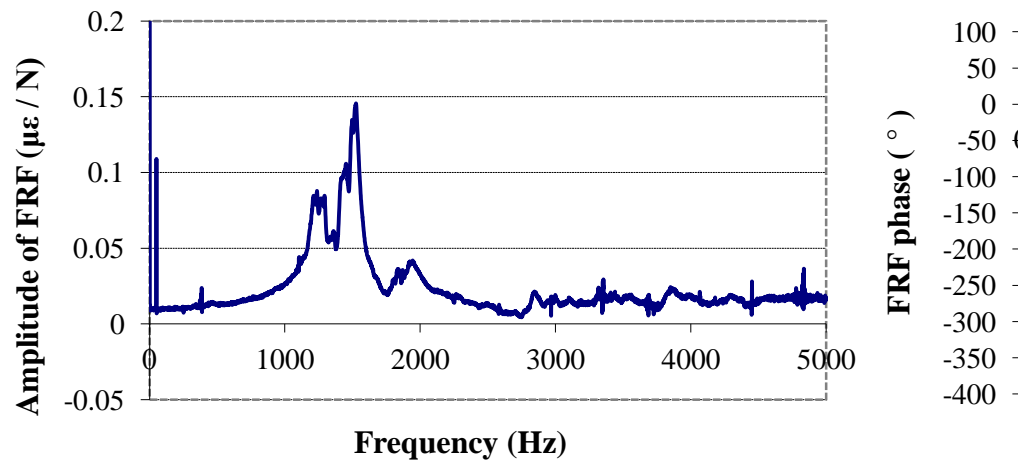
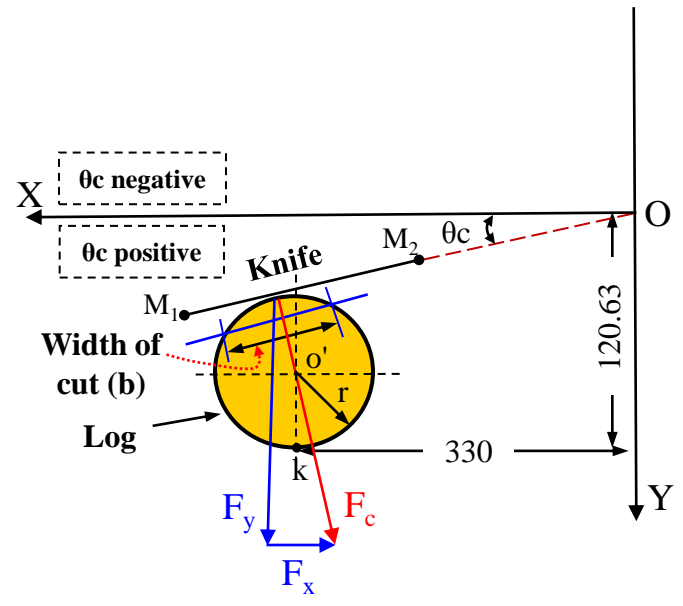


Figure 9





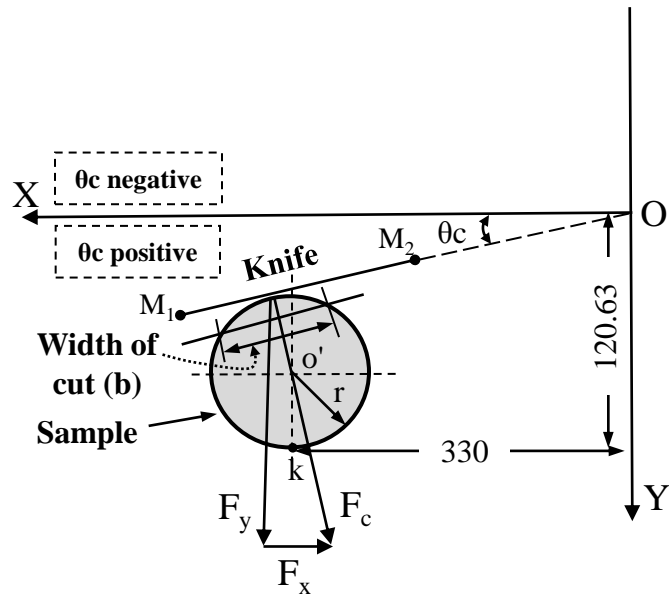


Figure 10

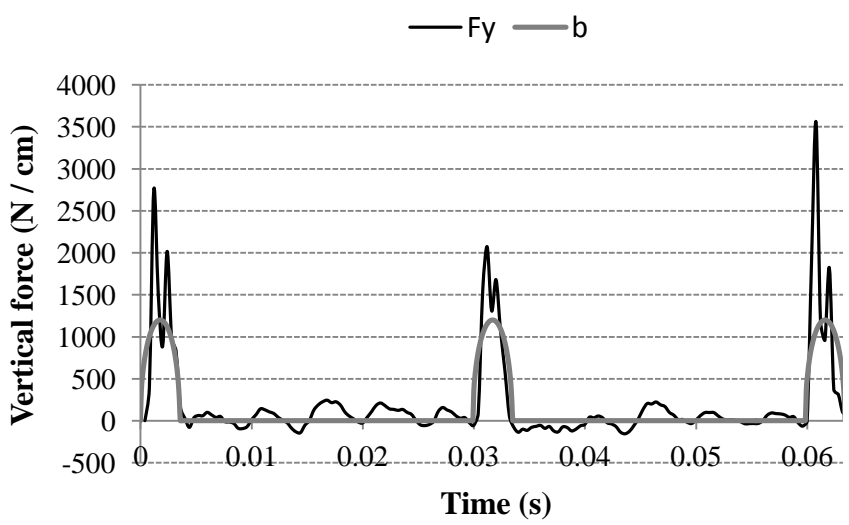
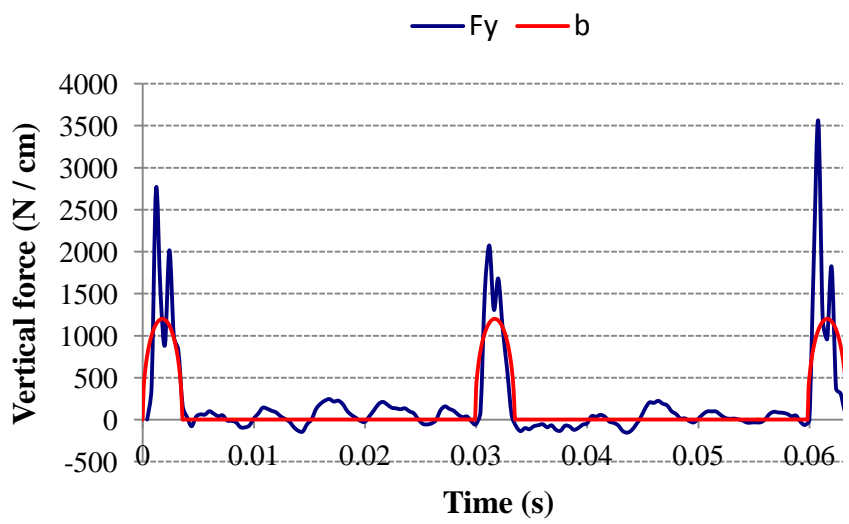


Figure 11

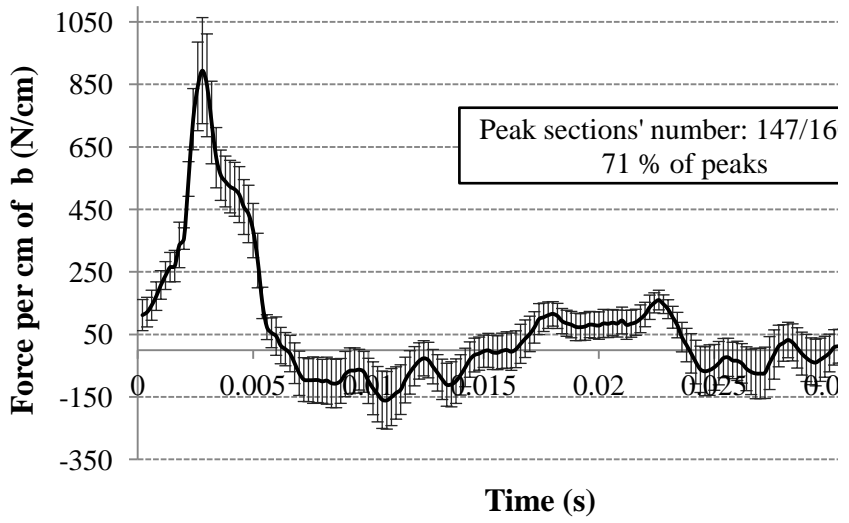
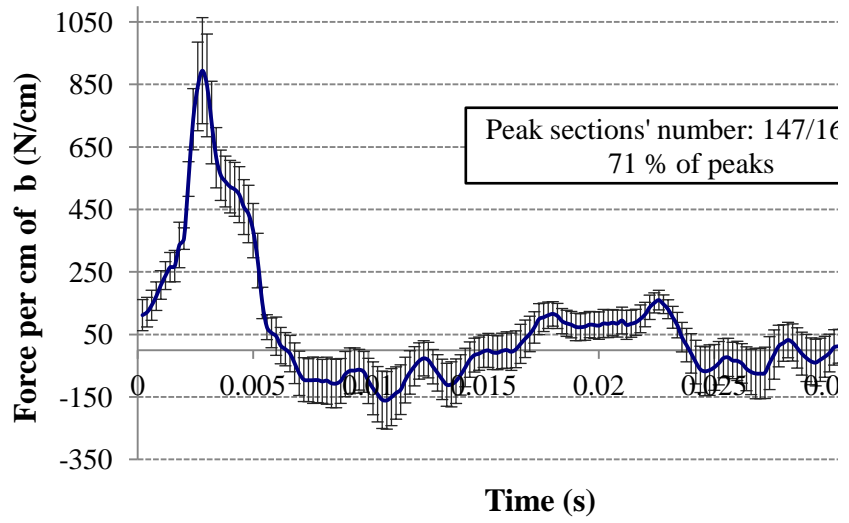


Figure 12

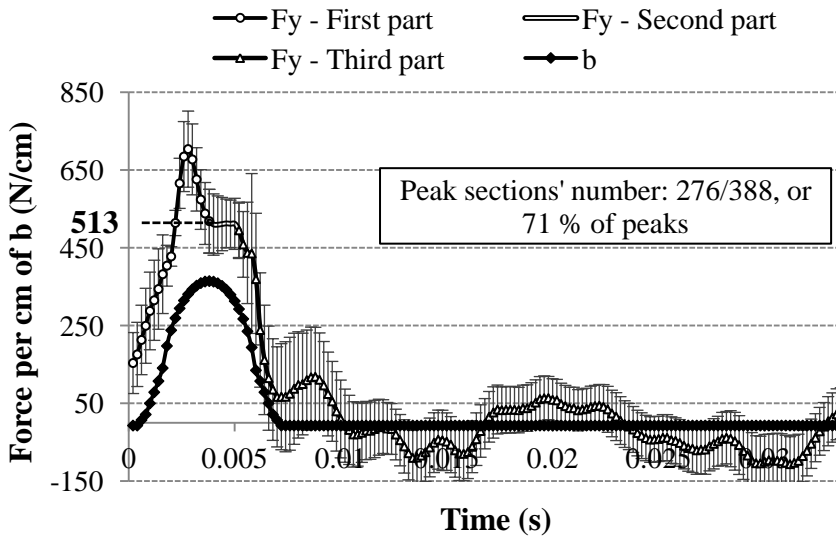
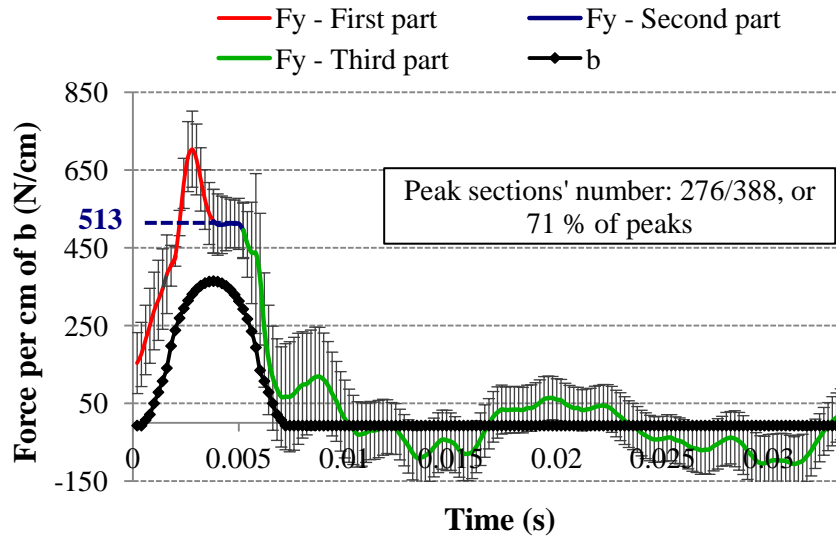


Figure 13

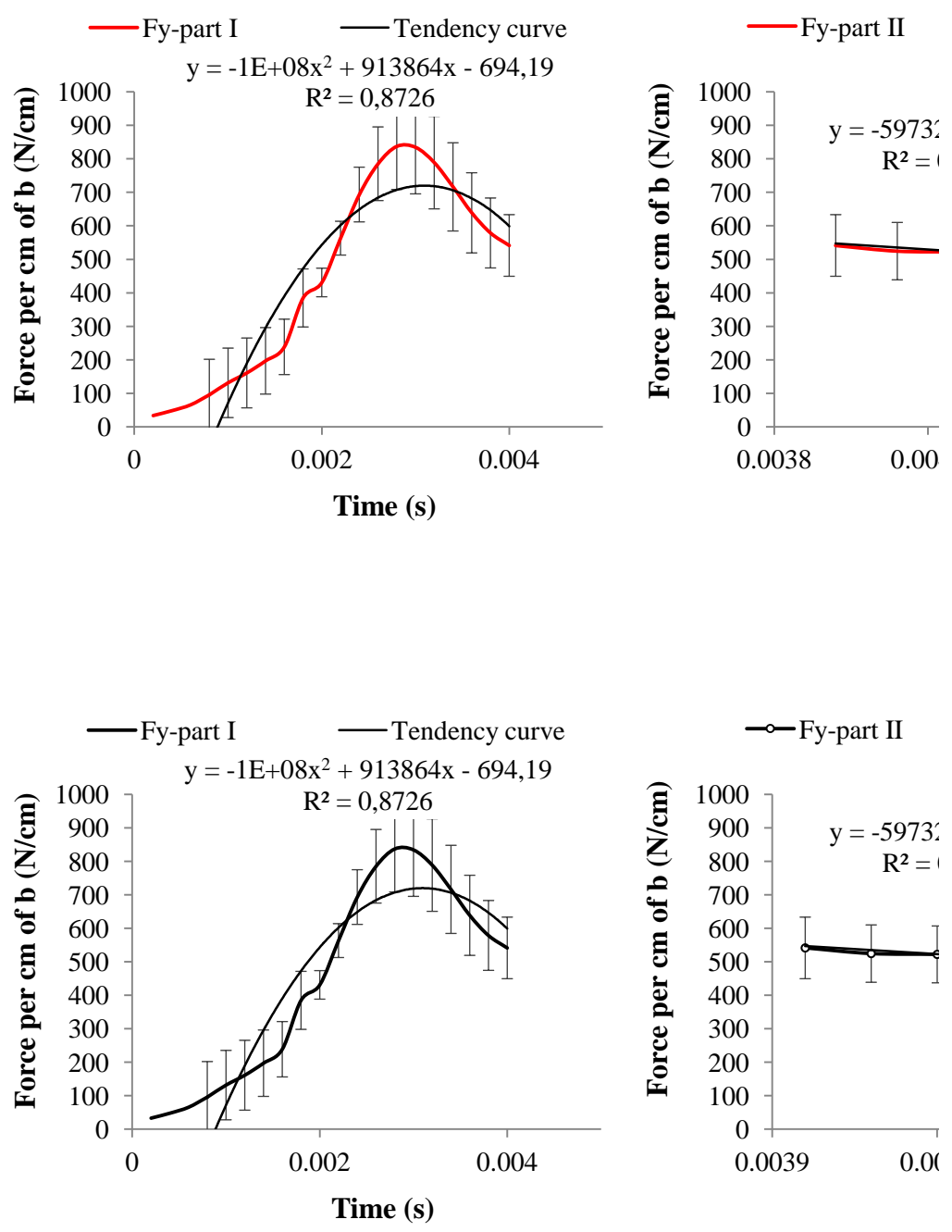


Figure 14

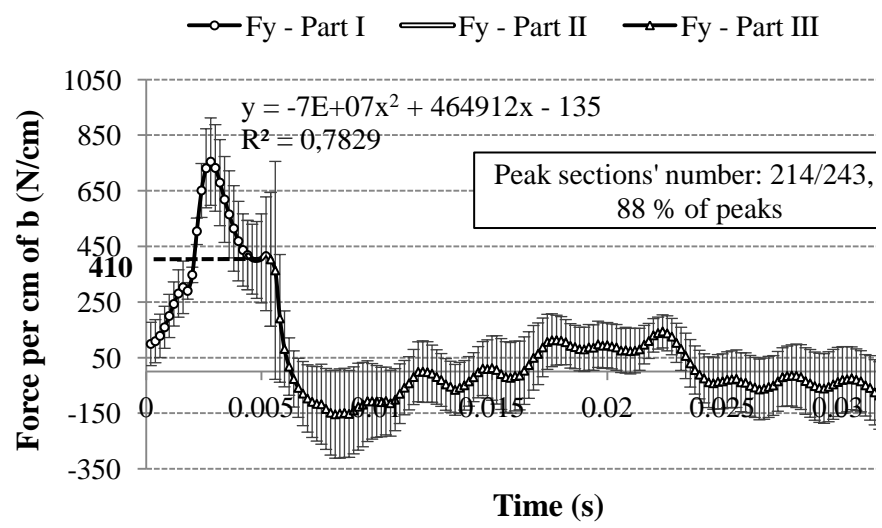
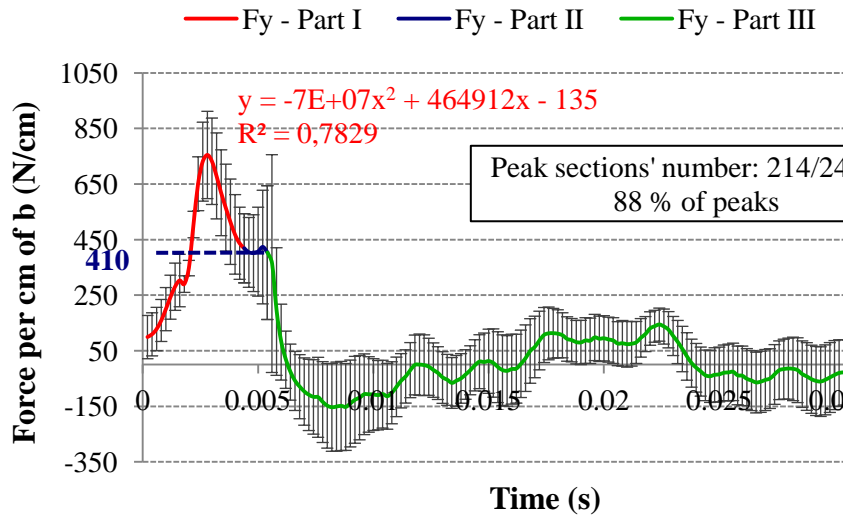
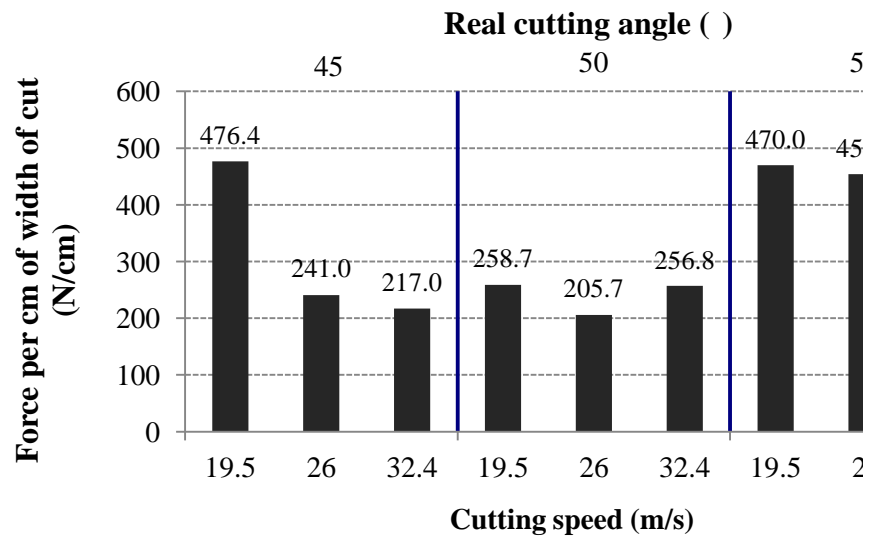
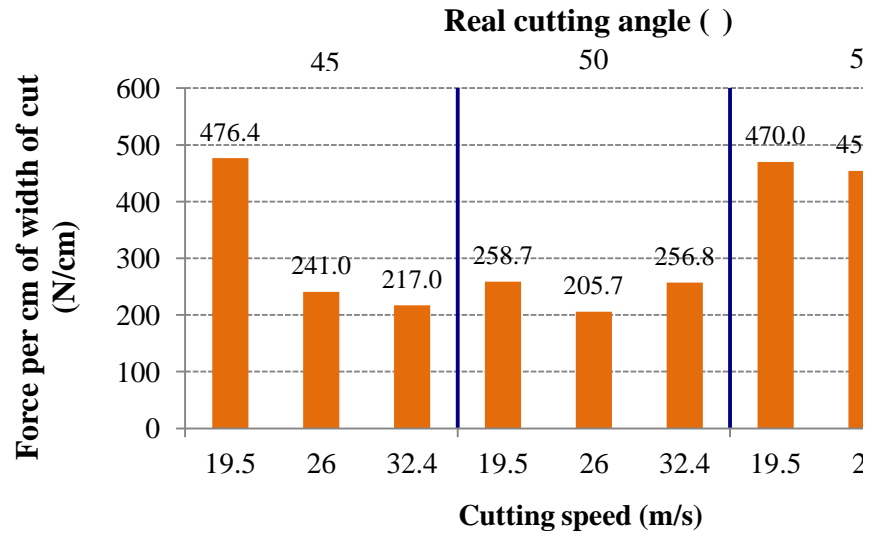


Figure 15



**“Color figures are intended for color reproduction on the Web only, and in black and white in print”**

**Figure captions:**

Fig 1. Cutting angles

Fig 2. Idealized diagram for the vertical chipping force component, proposed by Hartler [3]

Fig 3. Picture of the test bench

Fig 4. Cutting force components:  $F_x$ ,  $F_y$  and  $F_z$

Fig 5. Surface strain sensor (left), anvil with 2 strain sensors (right)

Fig 6. Anvil's longitudinal strain ( $\mu\epsilon$ )

Fig 7. Experimental arrangement ;  $E_j(t)$  denotes an excitation signal,  $S_i(t)$  denotes a response signal

Fig 8. Amplitude and phase of FRF

Fig 9. Cutting configurations

Fig 10. Vertical cutting forces  $F_y$  versus cutting width of cut

Fig 11. Example of averaged chipping force and its standard deviation per cm of cutting width (b)

Fig 12. Vertical force component ( $F_y$ ) with the variation of the width of cut (b)

Fig 13. Tendency curve of the first (left) and the second (right) sections of the force graph

Fig 14. Results of the force component  $F_y$  and its variation per cm of the width of cut

Fig 15. Cutting force  $F_y$  as a function of the angle  $\gamma_r$  and the cutting speed  $V_c$

**Table captions:**

Table 1. Values of the tested parameters

Table 2. Data of the  $F_y$  graphs resulting from the repeatability tests