Mechanisms of wood surface formation and resulting final condition after planing

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Mechanisms of Wood Surface Formation and Resulting Final Condition after Planing

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Abstract
In the framework of a research dealing with the quality of wood surfaces we aimed to develop a global approach to formation and quality of such surfaces. Some specimens of softwoods and of hardwoods have been processed in various machining conditions, including up- and down-milling, with several grain angles, along and against the grain. The results have been examined in order to evaluate the final quality of the surfaces, the types of the defects arising on the surfaces and the formation mechanisms. This paper highlights the main defects arising after planing wood and highlights the relationships between the grain direction, the wood density, the cutting mechanisms and the final quality, putting into evidence the surface response to processing.

1 Introduction

It is well known how one of the main factors involved in the surface final quality after processing wood is the grain direction. In facts processing at different grain directions as regards the worktable provides really different cutting conditions [3]. This difference is mainly connected to the differences in the cutting mechanisms due to the anisotropy of the material, consequently to the different properties of the wood in the different directions [2,4,6,7]. The authors have already described the mechanisms that characterise the cutting at different grain angles, but some more interesting connections seem to be possible for this matter. In facts the cutting mechanisms changes with the wood properties (density and moisture content mainly), the cutting technology and the grain direction. As a consequence, the final state of the surface evolves together with the cutting mechanisms. For this reason to every cutting mechanism can be connected a consequent final state of the surface, and in particular a visual defect. This work tries to present the main visual defects and the main cutting mechanisms, in order to give an idea of the connections existing between the two. This work should be considered as a "work in progress" and a first approach to the problem, the classification is a proposal that could be modified according to suggestions and following developments of the study.

2 Materials and methods

This study is the outcome of a long ensemble of tests carried out to study the surface defects and better understand the surface formation mechanisms [3]. The study has been divided in several phases: establishment of the processing settings, selection of different species to be processed, processing at various grain angles to achieve the formation of the defects, macroscopic, microscopic, SEM and profile analysis of the surfaces processed, visual analysis of the surfaces, analysis of the cutting mechanisms, classification of the cutting mechanisms, analysis of the cutting forces evolution when processing at different grain angles. The results presented in this paper have been obtained by processing different species (douglas fir, oak, beech, lime, poplar) at various grain angles up- and down-milling with and against the grain.

The tests at different grain angles have been carried out increasing by steps of 10° the grain angle after each test and conserving the processed surface in order to execute further analyses. For each species all the tests have been carried out in the same piece of wood, chosen with a regular grain. Each test started by processing at straight grain (0°) and ended by processing on the end-grain (90°). The intermediate angles were processed with the grain and against the grain (in the latter case, a "-"sign is placed before the angle). With this type of test it is possible to observe the formation of all possible defects that could arise from processing a piece of wood with given settings, making easy a complete description of the defects. In this paper no distinctions are made between different processing settings, but the target is to give a general idea of the mechanisms acting during the cutting and of the consequent visual defects, in order to put into evidence the probability of a defect to occur.

3 Results

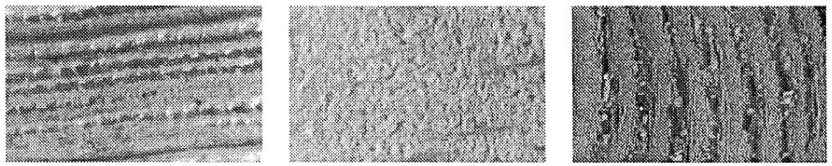
3.1 Definition of the defects

The first problem on which we should focus our attention is a clear definition for "defect". To get this definition we should firstly approach the "flaws" found on the processed surface.
A *flaw* of a surface is any feature differing from the "nominal surface" theoretically resulting from the processing.
In order to explain this definition, we have to clarify the concept of "nominal surface", that is the surface defined by the combination of the cutting and of the feeding motion during machining. Such surface is not necessarily flat, but may also have a complex shape.
The flaws of a surface can be divided in two main groups depending on their origin:

- anatomic flaws
- process flaws.

The origin of the anatomic flaws is directly connected with the anatomical structure (for example a surface can be rough because of the large earlywood vessels, like in the oaks), while the process flaws originate from the interaction between the wood's anatomical structure and the tool.
Firstly the flaws have to be qualified and quantified. It is important to establish the magnitude of the flaws referring to quantifiable entities. The main criterium used to qualify and quantify these flaws is a visual one, for this reason the evaluation scale has to be calibrated to the human eye. Actually any surface will result as irregular if observed through a magnification device; an essential factor is therefore the identification of a threshold. Such flaws can be classified according to their visibility as follows (see Figure 1):

- clearly visible flaws
- slightly perceivable flaws
- non perceivable flaws.



(a) Oak (10X) (b) Beech (12X) (c) Douglas fir (0,8X)

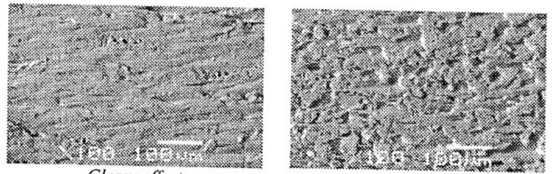
Figure 1: **(a)** *Anatomical flaw on the surface of oak.* **(b)** *A slightly perceivable flaw (Dull effect) processing beech against the grain.* **(c)** *A "clearly visible" flaw processing douglas fir, to be considered as a "processing defect".*

According to this classification, the "non perceivable" and the "anatomical flaws" will not be further discussed in the following, since they are not to be considered machining defects; for the same reason we will not further discuss the process-induced "slightly perceivable" flaws which results in the "glossy" and "dull" effect (see Figure 2). On the contrary, the discussion will deal with the process-induced and "clearly visible" flaws, which result into "defects".
We therefore define "machining defect" any deviation from a "nominal surface", directly caused by the machining, clearly visible to the human eye and other than the flaw originating purely from the anatomic structure. Machining defects can be evaluated according to the two following main criteria:

- according to the surface quality,
- according to their mechanical origin

The former approach identifies the defects according to their appearance, and defines different degrees of magnitude, whereas the latter gives a mechanical explanation of the surface origin, analysing the interaction between the tool and the material.
The defects can be classified according to general principles and assessed as:

- avoidable or unavoidable: if they can be avoided or not with a state-of-the-art machining
- gradable or non-gradable: if they can be graded according to their magnitude, or binarily
- common or specific: if they concern most wood species, or some specific ones only.

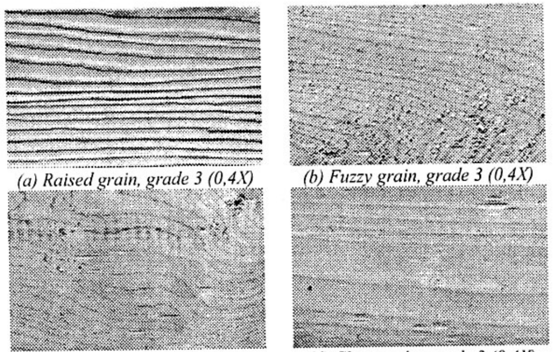


Glossy effect Dull effect

Figure 2: *Glossy and dull effect on douglas fir as classified by the authors.*

3.2 Visual grading of the defects

The visual grading of the defects has been standardised by ASTM D-1666-87 [1] (see Figure 3). In this paper our pourpose is not to describe this standard, but rather to present in general the machining defects in order to establish a connection with the wood cutting mechanisms. Although this standard is a really good tool for the description and grading of the defects, we found it is not sufficient to describe all kinds of machinig defects. For this reason we introduced some further defects, and we divided the defects in "principal" (see Figure 4 and 5) and "minor" (see Figure 6) according to the above mentioned general principles. Even if the principal defects are the more representative and important, the minor defects allows us to describe more properly a surface and make the correct connections with various mechanisms of surface formation.

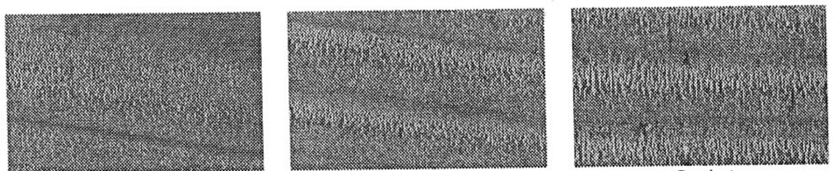


(a) Raised grain, grade 3 (0,4X) (b) Fuzzy grain, grade 3 (0,4X)

(c) Torn grain, grade 3 (0,4X) (d) Chip marks, grade 3 (0,4X)

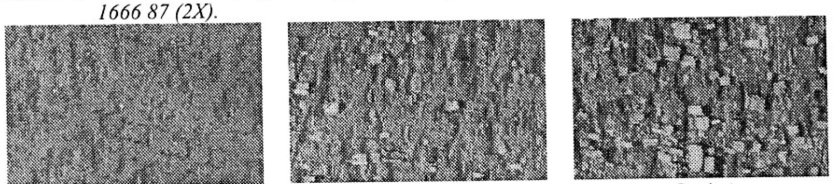
Figure 3: *The defects considered by ASTM D-1666 87 standard*

- Principal defects: according to our classification, they are "common" and "gradable". This group includes the defects considered by the ASTM standard (raised grain, fuzzy grain, torn grain, chip marks), and the additional ones defined by the authors, i.e. "pressed grain" and "tilted grain". The principal defects are listed below:
  - Raised grain
  - Fuzzy grain
  - Torn grain
  - Chip marks
  - Pressed grain
  - Tilted grain
- Minor defects: are defined as being "specific" and "non-gradable". Take part to this group:
  - Leaning earlywood
  - Hooked vessels
  - Hollow rays



Grade 2 Grade 3 Grade 4

Figure 4: *Classification of "pressed grain", a defect not previously classified by ASTM D-1666 87 (2X).*



Grade 2 Grade 3 Grade 4

Figure 5: *Classification of "tilted grain", a defect not previously classified by ASTM D-1666 87 (2X).*

(a) Leaning earlywood (2,5X) (b) Hooked vessels (10X) (c) Hollow rays (10X)

Figure 6: *Minor defects as classified by the authors on douglas fir (a), oak (b) and beech (c).*

The chip marks origin will not be taken into account in this paper because mainly influenced by the processing settings and by the suction system than by the wood properties.

3.3 Mechanical classification of surface origin

A mechanical classification of the surfaces origin has not been implemented yet by the scientists. Working on this subject we felt the need to introduce this classification because of many factors: defining correctly the cutting process, understanding better the final condition of the surface, analyse mechanically the process in order to develop new cutting strategies or to prevent the defects. For these reasons we began to study the basic stresses exerted by tool during the cut and we examined the wood elements reactions in the space applying these stresses in different directions. This study brought us to explain mechanically the surface formation at different grain angles with the different properties of the wood in the different sections and to improve a classification based on the evolution of the stresses during the cut (mechanisms chain) in a well determined zone (called functional zone). This part has been presented largely in a specific paper at this same conference, for this reason we will omit here to discuss this matter more deeply, referring the readers to the other paper called "Classification of wood surface defects according to their mechanical formation during machining". The principal formation mechanisms are summarised in Table 1.

Table 1: *The formation mechanisms as classified by the authors.*

Formation class	Principal mechanism	Secondary mechanism	Type
Material shifting	Transv. Tens.	partial failure	A1 (var. 1, 2)
		plastic failure	B1
	Transv. Comp.	elastic reaction	C1, C2, C3
		plastic failure	D1
Material detachment	Transv. Tens.	bending failure	E1 (var. 1, 2), E2
	Transv. Comp.	longitudinal tension failure	F1, F2 (var. 1,2)

3.4 Cutting mechanisms and "consequent" surface condition

After having presented the surface machining defects from the qualitative, quantitative and mechanical points of view, finally these aspects can be connected together. After the machining, each formation mechanism causes a different reaction of the wood and a different reorganisation of the surface, changing its final condition. For this reason the final condition (as visually graded) can be defined as "consequent" to a well defined mechanical process. We can discuss of "consequent defect" because we established a clear connection between the "mechanisms chain" and the final quality. The connection between the mechanical stresses and the consequent final condition is reported in Table 2.

Table 2: *Connections between the mechanisms chain and the visual final state of the processed surface. TC: transverse compression, TT: transverse tension, B: bending, AT: axial tension, AS: axial shear, TS: transverse shear, PP: plastic processes, EP: elastic processes.*

Mechanism type	Stresses	Consequent visual defect
A1 (var. 1 and 2)	TT/B	Fuzzy grain
B1	TT/B/PP	Pressed grain
C1	TC/EP	Leaning earlywood
C2	TC/EP	Hooked vessels
C3	TC/EP	Raised grain
D1	TC/PP	Glossy effect
E1 (var. 1)	TT/B	Torn grain
E1 (var. 2)	TT/B	Tilted grain
E2	TT/B	Torn grain
F1	TC/AT/AS	Torn grain
F2 (var. 1 and 2)	TC/AT/TS	Torn grain

These stresses have to be analysed also considering the processing technique, the processing settings and the wood properties, such as the grain direction, the moisture content, the density and its distribution within the rings. Some defects originate typically from processing with the grain, others from processing against the grain, others with a high density, other with a low density. Moreover high moisture content helps the plastic processes. The common conditions that originate a "mechanisms chain" resulting in the formation of the "consequent" visual defects are shown in Table 3.

Table 3: *Formation mechanisms, conditions inducing their occurrence and consequent resulting visual defect on the processed surfaces.*

Formation mechanisms	Density	Technology	Grain angle (°)	Consequent visual defect
A1 (var. 1)	Low	Up-mill.	-10/-30	Fuzzy grain
A1 (var. 2)	Low	Down-mill.	-10/-30	Fuzzy grain
B1	Indifferent	Up/Down-mill.	-30/-90	Pressed grain
C1	Heterogeneous	Up/Down-mill.	10/50	Leaning earlywood
C2	Indifferent	Up/Down-mill.	10/30	Hooked vessels
C3	Heterogeneous	Up/Down-mill.	30/70	Raised grain
D1	Medium	Up/Down-mill.	-10/-70	Glossy effect
E1 (var. 1)	Medium-high	Up-mill.	-10/-70	Torn grain
E1 (var. 2)	Medium-high	Down-mill.	-10/-80	Tilted grain
E2	Heterogeneous	Up-mill.	-10/-70	Torn grain
F1	Low	Up/Down-mill.	10/50	Torn grain
F2 (var. 1)	Low	Up-mill.	-60/-90 60/90	Torn grain
F2 (var. 2)	Low	Down-mill.	-60/-90 60/90	Torn grain

4 Conclusions

This paper aims to establish a new approach to the definition of the quality of wood surfaces machined by a turning tool; such new approach consists of considering and classifying the machining defects not only according to the surface quality, but to the mechanisms of surface formation as well.

Firstly, some definitions have been established, concerning the notion of flaw and defect. Some flaws have been recognized as not very significantly affecting the quality of the machined surfaces.

An accurate analysis of numerous surfaces, machined with various parameters, was the basis for analyzing the main visual defects resulting in processing wood at different grain angles. Traditionally the visual defects are defined by ASTM D 1666-87; we felt this standard not sufficient to describe all the range of defects that resulting by the tests, for this reason some additional defect has been defined, in order to better represent the whole range of defects actually perceivable on the machined surfaces. The defects have been divided in principals and minors in order to represent their role.

By the mechanical side we defined several mechanisms of formation of the surfaces. Such mechanisms have been classified and we shown how these mechanisms results in visual defect. This tight correlation shown between the final conditions of the surfaces and the mechanisms responsible of their formation allowed us to introduce the notion of defect "consequent" to a specific formation mechanism. Finally we analysed the conditions inducing the occurrence of a formation mechanism (processing technology, wood characteristics and grain angle) and so of a consequent surface final status.

This opens the way to a different approach to the cutting process and to the surface origin, by unifying the material science and the geometric analysis of the process. The surface formation conditions have been analyzed and connected to specific cutting mechanisms that have been classified and relayed to the final condition of the surface. This different approach to the cutting gives an improvement to the knowledge of the surface formation process, leading to the development of new cutting strategies.

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