MODELLING OF MULTI-LAYER
MATERIALS CUTTING

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S u m m a r y

The paper presents some aspects of modelling of multi-layer materials cutting process. Numerical calculation with the finite element method (Lagrangian equations) were performed for the decohesion process simulation of the example workpieces (machined with one tool wedge) consisted of two and three layers with different mechanical properties. Results of calculation in the form of colour maps of temperature and plastic strain fields distributions in the cutting zone are presented. An example course in time of the main cutting force components, during wedge tool passage through the different layers of the cutting material, is presented.

Keywords: modelling, cutting, multi-layer materials

Modelowanie skrawania materiałów wielowarstwowych

S t r e s z c z e n i e

W pracy omówiono wybrane zagadnienia modelowania procesu skrawania materiałów wielo-warstwowych. Obliczenia numeryczne metodą elementów skończonych (równania Lagrange'a) prowadzono w celu symulacji procesu dekohezji modelowych materiałów obrabianych. Materiały składają się z dwóch lub trzech warstw o różnych właściwościach mechanicznych. Obróbkę skrawaniem prowadzono za pomocą jednego ostrza narzędzia. Określono rozkłady wartości temperatury i odkształcenia plastycznego w strefie skrawania. Przedstawiono przykłady zmiany wartości składowych całkowitej siły skrawania podczas przejścia ostrza narzędzia między różnymi warstwami skrawanego materiału.

Słowa kluczowe: modelowanie, skrawanie, materiały wielowarstwowe

1. Introduction

Application of computer methods for designing of technological processes is necessary to fulfil today's high demands concerning accuracy and efficiency of the manufacturing process of machine parts, by removing layers of material from the workpiece with a cutting tool. The construction of machining simulation models enables speedy visualization of chip creation process in a wide range of machining parameters [1-3].

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Multi-layer material (called a composite) is a material with inhomogeneous structure, combined from two or more components with different properties. One of the constituent materials is a warp (matrix) bonding the composite into a whole and giving it hardness, elasticity and compression resistance. The other component of the composite is a structural material responsible for reinforcement of the composite by forming its other properties. In general, the role of the warp is to protect the reinforcing material, transfer external stresses onto it, and provide the required shape to the composite part produced, while function of the reinforcing material is reduced to secure high mechanical properties for the composite and reinforce the warp in selective directions [4]. Properties of the composite depend on the physical properties of the warp and those of the reinforcing material, form of a reinforcement (fibres, particles) and relative contents of the warp (V_o) and the reinforcement (V_w) formulated as volumetric fractions ($V_0 + V_w = 100\%$).

Composite materials can be divided into the following groups [5]:

• Structural composites – where continuous structures of the structural components occur – layers (e.g., plywood), rods (e.g., reinforced concrete) or regular three-dimensional structures, e.g., structures resembling a honeycomb.

• Laminates – which are composed of the fibres sealed into the binders – depending on the fibre order we can distinguish composite bands – fibres arranged in one direction – composite mats in two perpendicular directions – or composites with fibres arranged at random.

• Micro-composites and nano-composites – in which regular structure of two or more components is already arranged on the hyper molecular level – e.g., wood is a kind of the micro-composite, composed of the cellulose fibres twisted in bundles, "glued" by a lignin.

• Structural alloys – which are a kind of metal alloys, metals with non-metals, polymers with polymers and polymers with metals and non-metals with very regular microstructure, e.g., duralumin.

Properties of the composite with long and orderly fibres are definitely anisotropic. Long fibres can be unidirectional (all fibres parallel to each other) or weaved into a woven fabric form („preform" technique). Unidirectional location of fibres provides the highest mechanical properties to the composite.

Growing interest in composite materials – including mainly the fibrous composites – and the specificity of its structure cause the need to develop the rational methods for their machining. Composites are characterized by the non-homogeneous structure and anisotropy and are the materials with highly abrasive properties, which is the cause that machining involves many difficulties [5, 6].

In the case of precision cutting of different construction materials, like steel or other metal alloys we should also consider multi-layer workpieces of "*composite*" type [7-9]. Figure 1-2 show the differences between macro and micro scale of cutting.

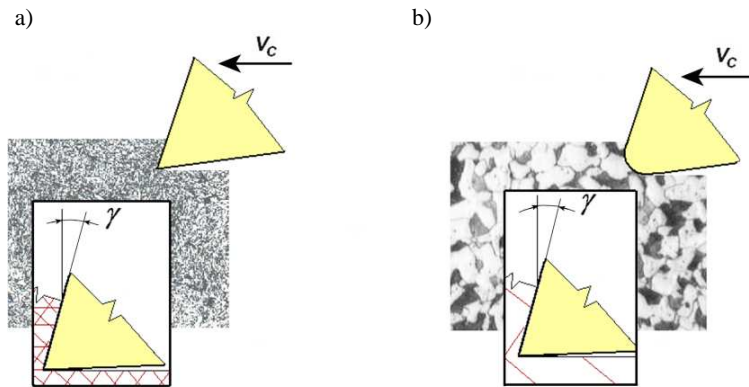a)   b)

Fig. 1. Relation between undeformed chip thickness h and grain size:
a) conventional size cutting, b) micro-cutting

During micro-cutting a chip is formed basing on the division of a single grain
(Fig. 1b) and the formed chip experiences a negative rake angle of high
modulus, Fig. 2b. In the conventional size cutting a cutting edge can be assumed
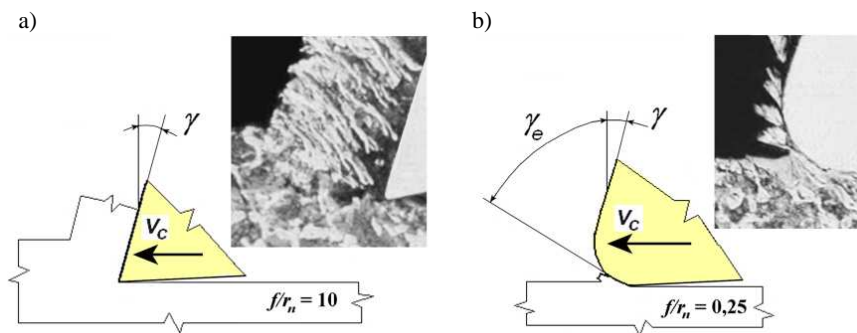as almost perfectly sharp and the actual rake angle corresponds to the nominal
one, Fig. 1a, 2a.

a)   b)

Fig. 2. Relation between undeformed chip thickness h and cutting edge radius r_n:
a) conventional size cutting, b) micro-cutting

The microstructure has a very strong influence on the chip formation
process [7]. Figure 3 shows the C45 steel with a relatively large grain structure
during decohesion process for different undeformed chip thickness, which can
be varied substantially through heat treatment and throughout the workpiece.
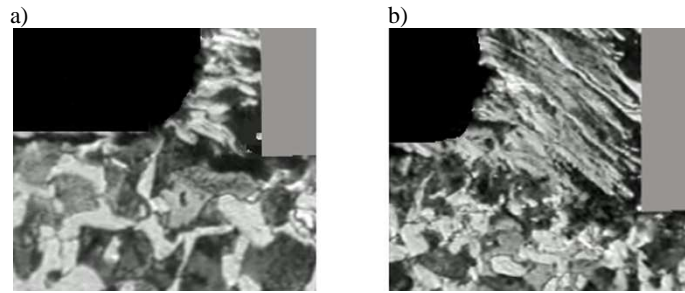The average ferrite grain size is about 10 µm while pearlite grains can exceed
100 µm.

Fig. 3. Optical images of the C45 steel microstructure during decohesion process for different undeformed chip thickness: a) $h = 0,02$ mm, b) $h = =0,05$ mm; larger pearlite grains (grey) and smaller ferrite grains (white)

Figure 4a presents a FE model, showing the micro-scale cutting across two different materials: bigger pearlite (A) and smaller ferrite (B) [8]. The general FE model is based on a number of basic assumptions. The cutting tool is assumed to be sharp even at such a small scale with no BUE. The material properties of A and B are meant to be rough approximations of a pearlite and ferrite microstructure respectively.
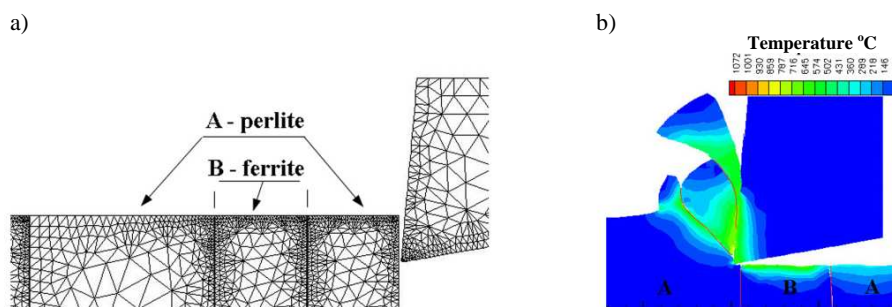

Fig. 4. Chip formation during micro-cutting: a) FE model showing the micro-scale cutting across two different materials (A – pearlite grain, B – ferrite grain), b) temperature distribution in the cutting zone

Basing on a numerical calculation a chip shape and temperature distribution in the micro-cutting zone were achieved, Fig. 4b. Cutting speed and feed were respectively: 300 m/min and 0,005 mm.

2. Modelling and simulation

Modelling researches embraced the working out of an analytical model of multi-layer materials decohesion process in condition of high speed shaping. Within the framework of numerical calculations a material strain analysis was taken. Model took into consideration the physical properties of the pair: tool

wedge-cutting material. The achieved distributions of temperature, stress and strain fields permit the virtual model determination of the decohesion process of specific composite materials. Lagrangian finite element method was used to simulation of the decohesion process [10]. Equation 1 presents the constitutive model by which the material will be governed.

$$\sigma(\varepsilon^p, \dot{\varepsilon}, T) = g(\varepsilon^p) * \Gamma(\dot{\varepsilon}) * \Theta(T) \tag{1}$$

where $g(\varepsilon^p)$ is strain hardening, $\Gamma(\dot{\varepsilon})$ is strain rate sensitivity and $\Theta(T)$ is thermal softening.

The composite material could crack during acting of the tool edge on it. The model of crack propagation in material consists of a curve fit (up to a 5-order polynomial) to a *Strain to Failure vs. Temperature* graph. The following equation (2) contains coefficients defining the *strain to failure* function.

$$\varepsilon_{f0}^p = d_0 + d_1 T + d_2 T^2 + d_3 T^3 + d_4 T^4 + d_5 T^5 \tag{2}$$

The results of an example computer simulation of decohesion process of two-ply workpiece (composite consists of horizontal layers) in the separate phases, in the form of temperature field distribution are presented in Fig. 5-7. *Layer 2* is about three times harder than *layer 1*, see Table 1. Cutting speed $v_c = 300$ m/min.

Table 1. Properties of two-ply workpiece

Properties	Layer 1	Layer 2
Yield strength	220 MPa	612 MPa
Hardness	110 BHN	305 BHN

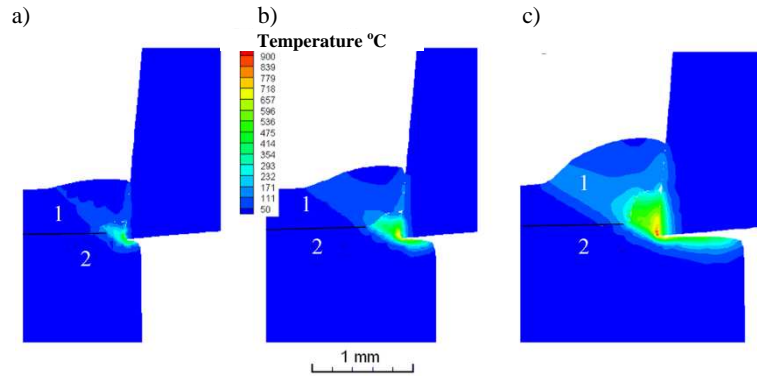Fig. 5. Model of decohesion zone – successive phases of decohesion process (a)÷(c)

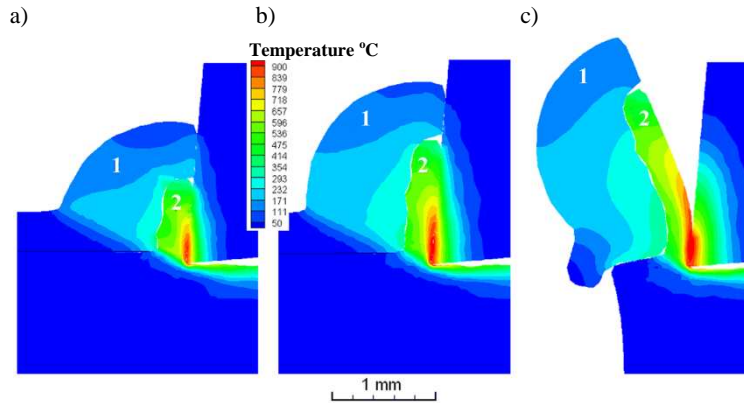a)   b)   c)

Fig. 6. Model of decohesion zone – successive phases of decohesion process, continuation (a)÷(c)
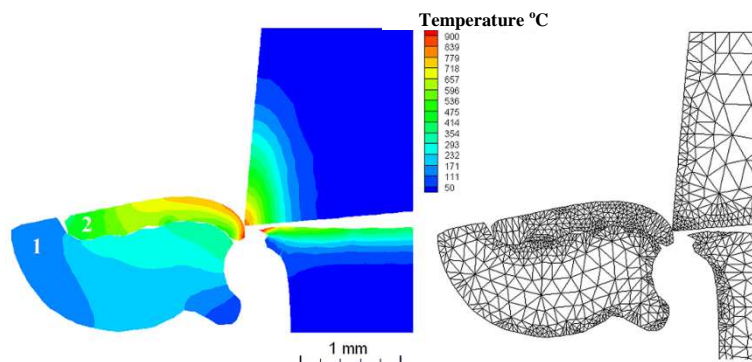

Fig. 7. Model of decohesion zone – the last phase of chip creation: a) temperature field
distribution, b) model with finite element net

Calculation values like chip compression ratio, maximum temperature and
plastic strain values in the chip body coming from different layers are presented
in Table 2. For comparison, Table 2 contains the same values but calculated for
homogenous model, built from only one material (as layer 2). Uncut chip
thickness was 0,1 mm. The other parameters were the same as for two-ply
workpiece.

Table 2. Chip compression ratio, maximum temperature and plastic strain values in the chip body
coming from different layers and from homogenous model

Chip coming from	Λ_h	T_{max}, ^{o}C	ε
Layer 1st (Upper part of the chip)	2,25	303	1,8
Layer 2nd (Bottom part of the chip)	3	852	5,6
Homogenous model (properties of layer 2)	2,1	770	5,3

The relative high chip compression ratio can be observed. The part of the chip, created from the more strength material (layer 2) possesses a higher chip compression ratio ($\Lambda_h = 3$) than in the case of homogenous model ($\Lambda_h = 2,1$). It results from the additional difficulties of the free chip flow, which is blocked by the upper layer of the two-ply model. The increase of normal force, acting on the rake face increases the friction force in this region, what causes the bigger value of the chip compression ratio and higher temperature in the cutting zone (852°C) (Fig. 8). The maximum plastic strain is bigger and exists in the bottom part of the chip, close to the cutting edge (5,6) (Fig. 9).
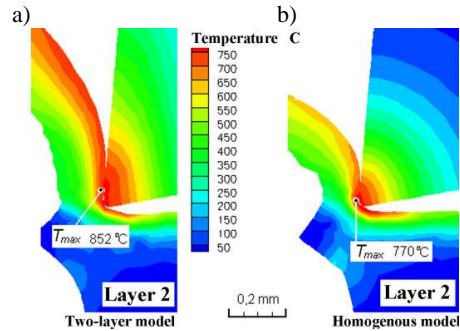

Fig. 8. Temperature field distribution in the workpiece for:
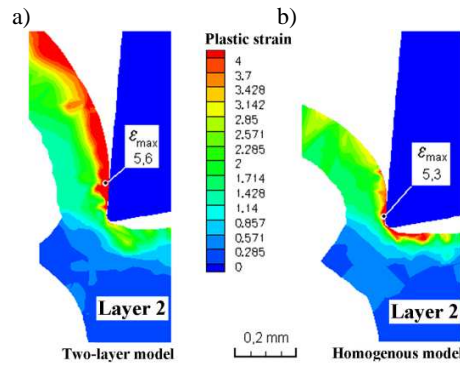a) two-ply model, b) homogenous model

Fig. 9. Plastic strain field distribution in the workpiece for:
a) two-ply model, b) homogenous model

The following example in Fig. 10-11 presents the model of decohesion process of composite substance, consisted of three vertical layers made of different materials (Tab. 3). Cutting speed $v_c = 75$ m/min. The courses in time of main force components F_x and F_y, during process are presented in Fig. 12.

Table 3. Properties of three-ply workpiece

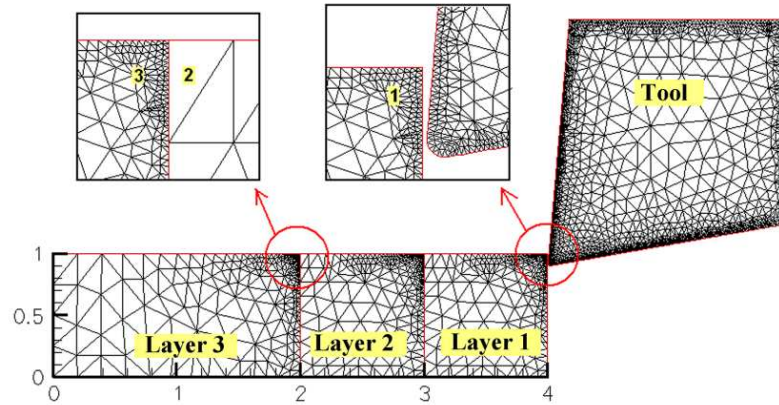| Properties	Layer 1	Layer 2	Layer 3
Yield strength	220 MPa	290 MPa	240 MPa
Hardness	110 BHN	205 BHN	180 BHN

Fig. 10. Model of three-ply decohesion zone (finite element net) – initial phase of decohesion process. Layers are placed perpendicular to the cutting speed vector
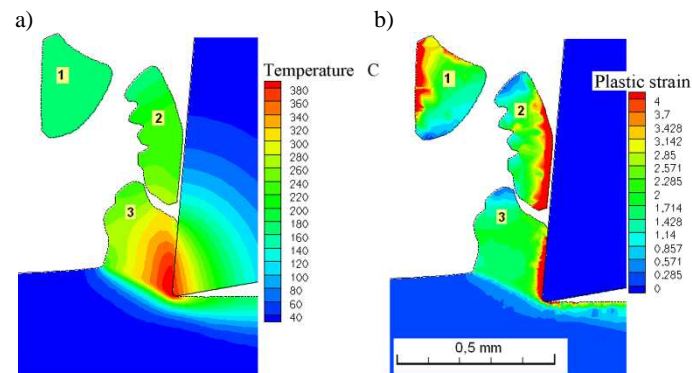

Fig. 11. Model of decohesion zone: a) temperature field distribution, b) plastic strain distribution

The chip after cutting consists of three parts. Cutting forces violently change their values in the moment of the beginning of the successive material cutting. Chip compression ratio, maximum temperature and plastic strain values in the chip body coming from different layers are presented in Table 4.
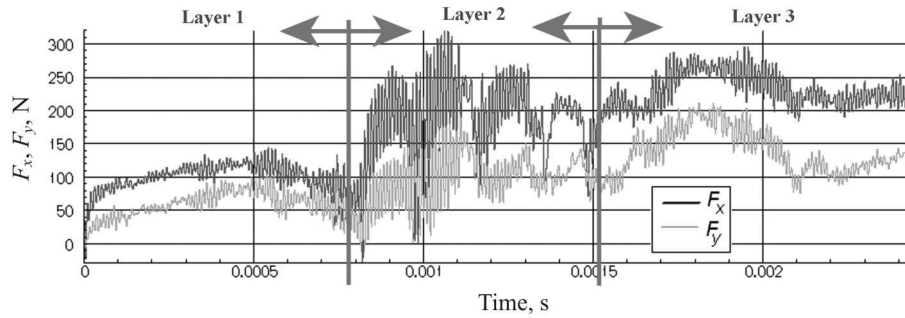
Fig. 12. Course in time of F_x and F_y main force components during decohesion process

Table 4. Chip compression ratio, maximum temperature and plastic strain values
in the chip body coming from different layers

Chip coming from	Λ_h	T_{max}, ^{o}C	ε
Layer 1st	3,25	274	6,9
Layer 2nd	2,1	410	4,1
Layer 3rd	3,4	415	6,8

3. Conclusions

In the case of composites we have to deal with multi-layer materials. Composites are particularly applied in the sectors such as aircraft, aerospace and automotive industries. Increasing application of these kind of materials causes the necessity of the rational methods of their forming. Modelling researches of the multi-layer workpieces permit the prognosis of the machined material behavior in non-typical conditions. The correct selection of the cutting parameters, in the situation of the cutting of materials with various physical proprieties (e.g. the alloy of aluminum and steel) with one tool is essential from the point of view of the surface quality and tool wear.

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