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Extension of the energy consumption model of mechanical chip-removal for precision and microcutting processes

PhD Thesis booklet

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The opinions of the referees and the material recorded at the defence will be available for viewing later at the Dean's Office of the Faculty of Mechanical Engineering, Budapest University of Technology and Economics.

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1. TOPIC AND AIMS OF RESEARCH

Mechanical cutting processes will still be one of the leading shaping methods of part manufacturing on the long term. Although there are some technologies, which generate the part's final geometry in a more direct way (e.g. precision die and sintering), there are special cases where appliance of such methods are not realizable due to specialities of part geometry (e.g. undercuts), mechanical and thermodynamic problems or unreasonably high costs. For such instances additional machining is needed to make the part meet technical and aesthetic requirements.

Miniaturisation is a general trend in modern part manufacturing. As sizes of everyday items are shrinking, so do the geometrical measures and related tolerance rates of the individual components. This circumstance lays claim to the appliance of precision and microcutting processes, while new, modern materials need to be machined. The update of technological database provided for production engineering is demanded in order to successfully adopt these technologies to the new requirements.

Specific components of the database are the predictive models of operation planning. With the assistance of these models, there is the opportunity to develop time- and cost-efficient machining processes. In order to achieve this goal, the models must present up-to-date and accurate information about the process to be realized, while they keep an easy- and quickly-to-apply characteristic.

Aim of my research is to extend the energy consumption model of cutting with geometrically defined cutting edge regarding the effect of cutting parameters. The direct outcome of my work is an updated version of the specific force model, which provides information about the characteristics of cutting force components on the domain of micro-sized uncut chip thickness, while keeping its suitability of appliance for macromachining. The updated model bears a mathematically continuous characteristic, which represents the significantly different nature of the energy consumption during macro- and microcutting based on information gained from the related literature and my own observations. The model also takes transients – like the entering and exiting of tool regarding the machined material – into account. I realized face milling and face-grooving turning tests in order to get data about the circumstances of cutting mentioned above.

2. BACKGROUND AND METHODS OF RESEARCH

It is still a leading choice to apply steel for constructions where parts need to be minimized regarding size and mass, while they can keep up against significant mechanical loads and maintain advantageous properties such as heat resistance and thermostability. Another reason of appliance standing by steel against other metallic and non-metallic materials is the better ability to withstand fatigue and fracture thus increasing the lifespan of the given part. Such causes swing the development of steels to reach higher tensile strength and yet maintaining auspicious specifications like preferable weldability and stiffness (similarly to unalloyed and low-alloyed steels). Development of high strength structural steels is a direct answer to the calls mentioned above.

Mechanical cutting is one of the most required methods of part shaping. This fact is heavily caused by bounds of executability of direct shaping processes and by the limits of size and geometrical tolerances of parts to be manufactured.

Miniaturisation is a general trend in part manufacturing as stated in [1]. This means not only the shrinking of sizes of parts but also – and more specifically – the sizes of geometrical features and the related rate of tolerance. To be able to create such delicate geometries there is a need for machine tools, which are suitable to move the cutting tool on a precise path. On the other hand, the tool's nominal sizes (e.g. diameter of micromilling cutters and microdrills) may have to be under the scale of 1 mm. Decreasing the size of the tool – thus making the tool more slender – means that it can withstand lower rates of mechanical loads. Appliance of these tools requires modification of cutting parameters as well. Such circumstances make the introduction of precision and microcutting processes necessary.

Precision cutting operations are processes where the required tolerance rate of the finished geometrical feature is under the scale of 0.01 mm. Although this criteria may require to set the uncut chip thickness into the micro-scaled domain, it does not exclusively mean that cutting parameters must be miniaturised nor specified tools should be applied. Furthermore, output process parameters (such as cutting forces) shows less transient and seemingly stochastic behaviour during precision cutting compared to those of micromachining.

Cutting with uncut chip thickness and uncut width of chip under the scale of 0.01 mm are identified as micromachining processes. Such conditions are initiated by carefully chosen cutting parameters: feed rate is characteristically set to the micro-scale as well thus limiting the extent of uncut chip thickness to the micro-scaled domain in every circumstances of cutting. However, microcutting is dealing with significant self-excitation as rate of mechanical loads are heavily depended on the local structural inhomogeneity and local deformations of material occurring at the chip's root thus generating feedback on vibrations. Furthermore, work hardening caused by deformation of the machined material is also significantly affecting the rate of energy consumption as stated in [2].

Prediction of mechanical loads during cutting is essentially needed to create correct and reliable machining processes. The predictive models of cutting allow to present correlations between input and output process parameters based on previously made specified measurements and plain observations taken during the everyday manufacturing. Basis of process planning is the optimisation of output parameters regarding the condition of part (e.g. surface roughness, accuracy of measures and features) and of the machining environment (e.g. tool wear) and time-consumption of manufacturing. Although this kind of output information describes the cutting process in a general way without distinguishing all the specific phenomena leading to the current conditions, the output parameters are heavily and directly determined by the mechanisms of chip-creation. Thus, it is crucial to condition the cutting parameters even before the beginning of actual cutting. An indicative and effective solution of conditioning is provided by empirical models, which are describing the characteristics of energy consumption of cutting i.e. the rate of energy dissipated by mechanical and thermal mechanisms during a defined time-period of cutting. Amount of required energy is depended on specifications of the cutting environment (e.g. material properties of tool and of machined material, cutting edge geometry, cutting parameters). Cutting energy can be determined indirectly by measurement of output parameters (e.g. cutting force) therefore it can provide depiction of the characteristics of process parameters from the aspect of effect dealt by the geometrical and kinematical conditions. Such modelling is called as the Specific Energy Consumption (SEC) method, which contribute predictive models to process planning being valid on an extended set of input parameters during a given cutting technology and cutting conditions as it is show in [3]–[5]. Models of SEC are primarily dealing with practical interpretation. Therefore, these expressions are not derived from standard laws of physics or of its subtopics (e.g. material science, dynamics) but are focusing on the simplistic portrayal of correlations between input and output parameters of cutting.

A representative indicator of cutting energy consumption is the specific cutting force. It determines the amount of cutting force (which is parallel to the direction of cutting speed) required to remove chip section of a unit:

$$k_c = \frac{F_c}{A} = \frac{F_c}{h \cdot b} \approx \frac{k_1}{h^{x_k}} + \text{const} \tag{1}$$

where k_c (N/mm^2) is the specific cutting force, F_c (N) is the cutting force, A (mm^2) is the uncut (or undeformed) chip section, h (mm) is the uncut chip thickness, b (mm) is the uncut width of chip, k_1 and x_k are empirical modelling constants [6]. Rate of cutting force depends on the machined material's mechanical resistance against deformation, which – in case of metals produced by metallurgy – depends primarily on yield strength and hardness. However, these material properties change due to work hardening caused by deformation. Furthermore, there are intense outer friction called as ploughing (between part and tool) and inner friction in the deformation zone of the machined material. The k_c specific cutting force shows a nonlinear characteristic against uncut chip section (which phenomena is called as *size effect*) and even the characteristic itself changes significantly between specified domains of uncut chip thickness. Such nonlinearities are described by the multi-sectioned model of specific cutting force (see Fig. 1.).

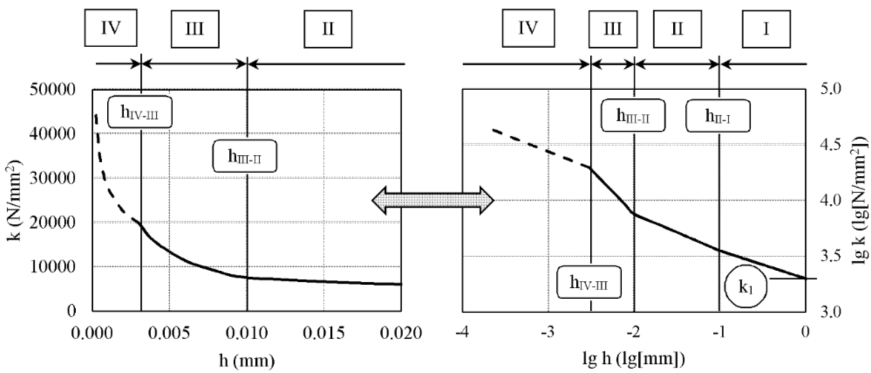

Fig. 1.: Multi-partitioned model of specific cutting force [B1, pp. 2737]

Considering the fact that specific cutting force is proportional to the cutting energy, characteristics of the different sections of specific force may indicate a change of type of material deformation as presented in [7] – [9]. Therefore, direct aim of my research was to describe the specific cutting force of machining with micro-scaled uncut chip thickness, identify of section IV (as shown on Fig. Fig. 1.) and reveal its the nature compared to those other sections, which are already well documented.

3. SUMMARY OF RESEARCH

Direct aim of my research is to extend the multi-sectioned model of specific cutting force to the domain of h < 0.01 mm uncut chip thickness regarding the effect of cutting parameters. Benefit of this approach is a renewed model, which is suitable to

- give reliable prediction about cutting force thus cutting energy needed to sustain the process of microcutting, while the model keeps its validity for macrocutting, and to
- make critical circumstances of cutting to be revealed where the type of material deformation in the chip's root shows significant changes.

Cutting tests were designed in order to reach my goals mentioned above during which the cutting parameters were systematically changed. Data required for creation of the model was acquired from cutting force measurement during machining of S960QL high strength structural steel of which mechanical properties were defined by tensile testing and measurement of micro-Vickers hardness. Furthermore, pictures of material were taken by microscope in order to examine its actual structure. All the material testing were realized at the Department of Materials Science and Engineering of BME.

Face milling tests were accomplished in order to be able to directly examine the characteristic of specific cutting force against the uncut chip thickness (described as a $k(h)$ function). Due to the kinematics of milling the uncut chip thickness is not an individual factor of experiment but a dependent variable of which extent is determined by the feed rate of the cutting edge and it changes in a recurring way as per periods of the tool's rotation. Resolution of the domain of uncut chip thickness regarding force measurement is proportional to the frequency of measurement (or frequency of data acquisition), hence the applied frequency was determined by the number of tool's rotations per seconds. Face milling was performed by Sumitomo WEX AXMT123504PEER-G cemented carbide insert placed in Sumitomo WEX 2016 E type of tool body. The tool had the nominal diameter of 16 mm and possessed one single cutting edge in order to avoid superpositioning of cutting forces that may have occur on different edges simultaneously. Machining was accomplished on Kondia B640 machining centre, force measurement was realized by Kistler 9257A 3-component piezoelectric sensor and Kistler 5019 charge amplifier. Data registering was made by National Instrument UBS-4431 data acquisition box. Angular position of the cutting edge – where the centre of angle was identical to the axis of tool's rotation – was checked by Omron E3F-DS10B4 type capacitive proximity sensor. Face milling tests were carried out at the CNC Laboratory of the Department of Manufacturing Science and Engineering of BME. The list of cutting parameters is presented in Table 1 where notations stand for parameters as follows: v_c – cutting speed, f_z – feed rate of cutting edge, a_p – axial immersion (depth of cut), a_e – radial immersion (width of cut), *DIR* – kinematical direction of milling. An amount of 90 individual cutting tests were realized at different settings of parameters.

Table 1. Factors and their levels in the face milling tests

No.	v_c, m/min	f_z, mm/(1·1)	a_p, mm	a_e, mm	*DIR*
1	50	0.01	0.5	8	down
2	75	0.04	1.0		up
3	100	0.16	2.0		
4	125				
5	150				

Evaluation of force measurement data was accomplished according to my goals of modelling (as depicted on Fig. 1). The following conclusions were established:

1. A new section boundary of specific cutting force is to be identified at the uncut chip thickness of $h_{III\text{-}IV}$. This new boundary is clearly distinguishable from other documented boundaries. Therefore, the existence of the new boundary is firm and it can be profoundly identified by evaluation of measured data.
2. I developed an iterative method to identify the locations of specific force boundaries. Results show that the method is suitable to fulfil its purpose of creation.
3. Each vector-component of the resultant force of cutting (namely cutting force (*c*), normal force (*n*) and passive force (*p*)) bear the similarities regarding section boundaries, including the newly identified one (see Fig. 2). Therefore, it is profound to state that the multi-sectioned

characteristics of specific cutting force is representative to the other specific force components as well.

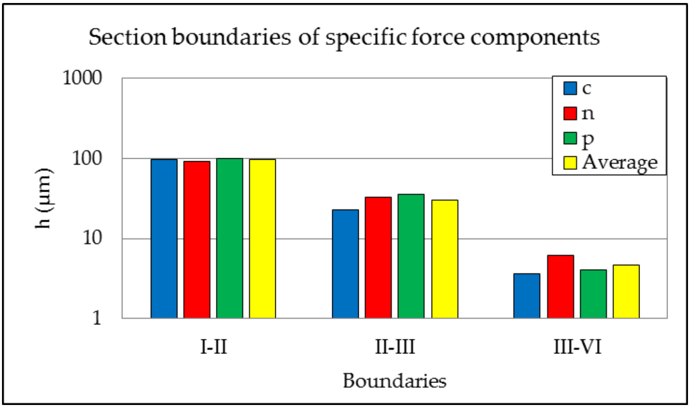

Fig. 2. Section boundaries of force of cutting

Effect of cutting parameters on the location of section boundaries was examined by ANOVA (Analysis of Variance). Based on results I made the following statements:

- Feed rate has the most significant effect on the locations of section boundaries. An increasing feed rate causes the boundaries to be relocated to a bigger uncut chip thickness.
- Uncut width of chip has no profoundly identifiable effect on the location of boundaries regarding current set of measured data.
- Cutting speed has a specific effect on the boundary at $h_{III\text{-}IV}$. An increasing cutting speed causes the boundary to be relocated to a bigger uncut chip thickness, although this effect is much more moderate as of feed rate.
- Kinematical direction of milling has a very moderate effect on the locations of boundaries as the effect is smaller by scales compared to those of feed rate and cutting speed, regarding the boundary at $h_{II\text{-}III}$ especially.

Taking the observations into account, I concluded that the model of the locations of boundaries at $h_{II\text{-}III}$ and $h_{III\text{-}IV}$ requires the feed rate and cutting speed as input parameters. The related result are presented on Fig. 3 and 4 (applying notations of Fig. 1).

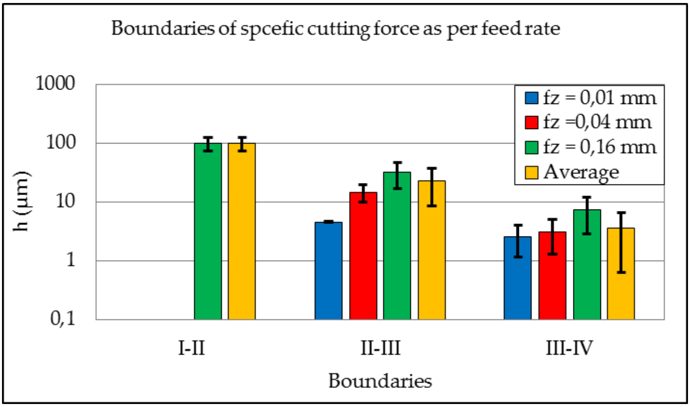

Fig. 3. Section boundaries of cutting force as per feed rate

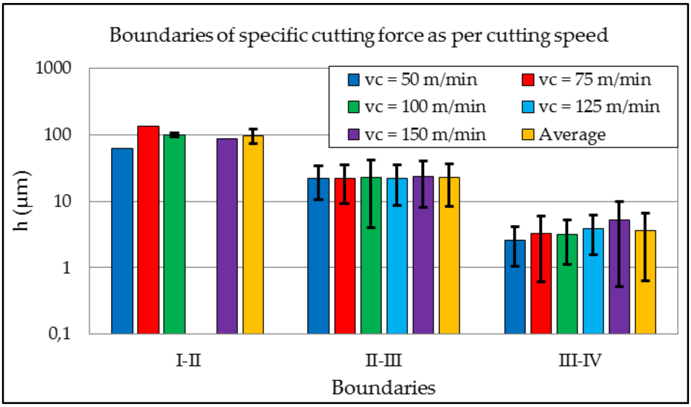

Fig. 4. Section boundaries of cutting force as per cutting speed

The presented results are indirectly in accordance with the statements of other researches such as [7], [8] and [10]. Hence I have the conclusion that the methods of measurement and evaluation are suitable to fulfil the purposes of current research. These methods are implemented into a unique software, which I specifically developed according to aspects and circumstances of current work.

In order validate the result of face milling, face-grooving turning tests were carried out. Face grooving is a suitable method the measure not only forces awakened by cutting but also the geometry of the undeformed chip section following the machining process (in contrast with milling where the option of measuring the actual uncut chip section is not available and models are required to be applied, instead). Aim of the turning test was to gain data regarding the characteristics of specific cutting force comparable to those acquired from face milling. Therefore, the circumstances of cutting during face grooving had to beer great similarities to the environment of face milling. The turning tool (Seco 10EAR2.5FA cemented carbide insert with Seco CEAR2525M10D tool body) chosen accordingly based on its cutting geometry. The uncut width of chip was determined by the width of the cutting edge, while the uncut chip thickness was set by parameters related to the kinematics of cutting. Chip-removal was accomplished on constant diameter per tests and had to be concluded within one single rotation of part in order to avoid re-machining of groove. Deformation of chip at up- and down-milling was simulated by the entering and exiting phrases of grooving, respectively. Such tests required precise positioning and movement of tool. Therefore, turning test were carried out on a Hembrug Mikroturn 50 ultra-precision CNC-lathe. Force measurement was realized by Kistler 9257A sensor and Kistler 8050A charge amplifier accompanied by National Instruments USB-4431 data acquisition box. Angular position of part was checked by Omron E3F-DS10B4 proximity sensor. The face-grooving turning tests were carried out in the Ultra-precision and micromachining Laboratory of the Department of Manufacturing Science and Engineering of BME. The applied set of parameters is presented in Table 2 where notations stand for parameters as follows: v_c – cutting speed, Z_{max} – maximum working depth, χ – number of ratio to determ the extent of the part's angular movement as $\chi \cdot 2\pi$ in which cutting must be fully accomplished.

Table 2. Factors and their levels in the face-grooving turning tests

No.	v_c, m/min	Z_{max}, mm	χ, 1
1	50	0.01	0.75
2	100	0.02	
3	150	0.04	

I measured the profile of the groove with Mitutoyo Surftest SJ-401 profilometer and surface roughness tester in given angular positions of part in order to define uncut chip thickness and uncut width of chip. Positions of profile measurements and force registration – all defined in the part's polar coordinate system – was aligned by the help of the proximity sensor's signal. Thus, specific cutting force was calculated. The following statements were made after the evaluation of data:

- Sections of specific cutting force and the locations of their boundaries in face-grooving turning bear great similarities to those defined in face milling. Examples of comparing results of turning and milling are shown on Fig. 5 (where "M" stands for milling and "T" for turning).
- Therefore, the realized face-grooving turning tests are suitable to simulate the circumstances of milling's energy consumption. To do so, it is essentially necessary to provide similar cutting conditions for both technologies.
- Furthermore, the specific cutting force as per uncut chip thickness can be successfully defined by the realized turning tests regarding an extended set of cutting parameters.

The presented results are indirectly in accordance with the statements of other researches such as [11]. Conclusions of turning tests proved that the new section boundary of specific cutting force (identified with milling) does exist. The boundary can be located by the corresponding uncut chip thickness in case of different technologies of cutting with geometrically defined edge.

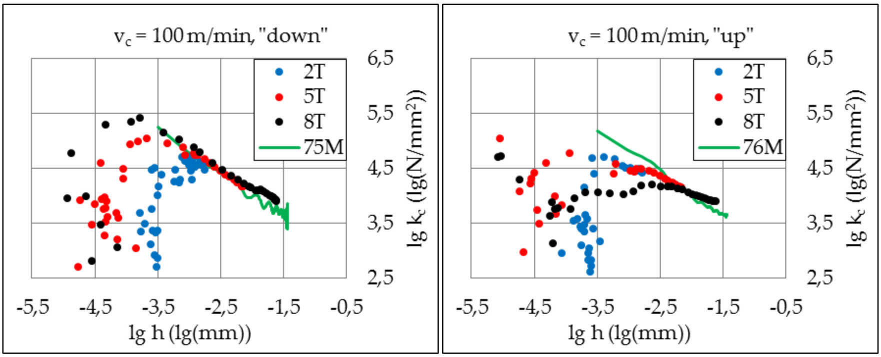

Fig. 5. Comparison of specific cutting forces acquired from milling and turning tests

Result of face milling and face-grooving turning indicate that the new section boundary of specific cutting force is not identical to the minimum uncut chip thickness, which is defined as the lower limit of applicable settings to provide stable chip-removal. The new boundary indicated the lowest uncut chip thickness required to perform any material removal. There is no material removal below the given uncut chip thickness but an intense local elastic and plastic deformation of the part surface. Furthermore, the characteristic of specific cutting force significantly changes at this boundary. It is observable on Fig. 5 that decreasing the uncut chip thickness causes the specific force to increase degressively to the point of boundary. However, further decreasing the uncut chip thickness results a progressive fall of specific force. This phenomena indicates the possibility to resolve a modelling problem of the specific cutting force. The specific force model is formed as a power function, and – as uncut chip thickness goes to zero – the model's limit is mathematically infinite due to the function's monotone characteristics Regarding the cutting process in reality, limit of the model should approach zero. Evaluation of face-grooving turning was accomplished by a unique software suit, which I developed specifically for the purposes and adopted to the circumstances of current research.

4. THESIS POINTS

The following scientific statements could be established based on the evaluated results of my face milling and face-grooving turining tests:

THESIS 1: In the case of cutting of S960QL high strength structural steel with geometrically defined cutting edge, a boundary of sections can be identified in the diagram of the specific cutting force as function of *h* uncut chip thickness on the domain of $h < 0.01$ mm as well.

My [B1], [B4] and [B7] publications are related to Thesis 1.

THEZIS 2: Under given machining conditions, regarding the cutting of a given material with geometrically defined cutting edge, sections of the specific cutting force model and the locations of section boundaries can be determined with significantly less number of cutting tests (compared to those commonly applied ones, which are carried out as cutting with constant uncut chip section geometry) by the following procedure, while handling also transient processes occurring during material shaping:

- **Under constant machining conditions, force components – which are defined in the orthogonal coordinate system attached to the cutting edge as cutting force, normal force and passive force, and which are arisen by chip-removal – must be measured during face milling operation.**
- **Force measurement must be realized uninterruptedly for multiple periods of tool rotation, where the frequency of data acquisition is an integer multiple of the number of tool revolutions per seconds and the**

angular position of the cutting edge in the moment of force-data acquisition is registered simultaneously.

- **Representative value of forces at the given angular position of cutting edge must be defined as the arithmetic mean of force values measured at the same angular position within each examined rotation.**
- **Specific components of force (specified on the uncut chip section) must be determined at the given angular position and localised by uncut chip thickness.**
- **Based on the previously created data set of pairs of points, locations of section boundaries within the specific force model can be defined as follows:**
  1. **Assumed locations of section boundaries must be given manually.**
  2. **The regression model of**

     $$k = f(h)$$

     must be fitted separately on data belonging to each manually defined section, where *k* (N/mm²) is the specific force component, *h* (mm) is the uncut chip thickness.
  3. **The form of objective function of section boundaries' locations is as follows:**

     $$\mu = 1 - \frac{h_{intersection,i,i+1}(k_i = k_{i+1})}{h_{manual,i,i+1}} \rightarrow \min$$

     where *i* is the identification number of the specific force model's sections, $h_{manual,i,i+1}$ (mm) is the assumed location of section boundary between the sections No. *i* and *i*+1, $h_{intersection,i,i+1}$ (mm) is the section boundary defined by the analytically calculated intersection of sections No. *i* and *i*+1, μ (1) is the relative difference between the assumed and calculated location of section boundaries.

My [B1]–[B4], [B6], [B7] and [B9]–[B11] publications are related to Thesis 2.

THESIS 3: In the case of cutting of S960QL high strength structural steel with geometrically defined cutting edge, location of the section boundary within the model of specific cutting force as function of *h* uncut chip thickness on the domain of *h* < 0.01 mm depends primarily on feed per cutting edge. Correlation of the boundary's location and feed per cutting edge is described as follows:

$$h_{III-IV} = C_{h,f} \cdot f_z^{x_h}$$

where h_{III-IV} (μm) is the uncut chip thickness, which defines the location of boundary, f_z (mm/(1·1)) is the feed as per cutting edge, $C_{h,f}$ and x_h are constants of regression. In case of dry face milling process with feed per cutting edge in the range of f_z = 0.01…0.16 mm/(1·1) the constants are defined as follows:

$C_{h,f}$ = 11.6 és x_h = 0.51

My [B1], [B4] és [B8] publications are related to Thesis 3.

THESIS 4: In the case of cutting of S960QL high strength structural steel with geometrically defined cutting edge, location of the section boundary within the model of specific cutting force as per *h* uncut chip thickness on the domain of *h* < 0.01 mm does depend on the cutting speed. Correlation of the boundary's location and cutting speed is described as follows:

$$h_{III-IV} = C_{h,v} \cdot v_c^{z_h}$$

where h_{III-IV} (μm) is the uncut chip thickness, which defines the location of boundary, v_c (m/min) is the cutting speed, $C_{h,v}$ and z_h are constants of regression. In the case of dry face milling process with feed per cutting edge in the range of f_z = 0.01…0.16 mm/(1·1) and v_c = 50…150 m/min the constants are defined as follows:

$C_{h,v}$ = 0.2 és z_h = 0.551

My [B1], [B4]–[B6] és [B8] publications are related to Thesis 4.

THESIS 5: Results gained from face milling and face-grooving turning tests and information acquired from the related literature indicate that the uncut, undeformed chip thickness defining the location of section boundary on the uncut chip thickness domain of *h* < 0.01 mm marks the lower limit of technology settings, which allows any material removal. This uncut chip thickness is not identical to the minimum uncut chip thickness, which marks the lower limit of technology settings of performing stable material removal.

THESIS 6: Under given machining conditions, in the case of cutting of a given material with geometrically defined cutting edge, determination of specific cutting force as a function of uncut chip thickness and identification of transient processes occurring during material shaping can be realized by the following procedure:

- **Under constant machining conditions, force components – which are defined in the orthogonal coordinate system attached to the cutting edge as cutting force, thrust force and passive force, and which are arisen by chip-removal – must be measured during face-grooving turning operation performed on constant working diameter where the profile of the cutting tool's primary edge is a line parallel to the face of test part and any cutting is realized within one rotation of the part.**
- **Angular position of the test part must be registered simultaneously to force data acquisition by proximity sensor.**
- **Profile of groove section created by turning process must be measured in the plane perpendicular to the face of the part and perpendicularly to the projection of the directrix of the groove defined in the plane parallel to the face of the part as well.**
- **Undeformed chip section at the location of profile measurement is determined as**

  $$A = \left| \int_{x_{start}}^{x_{end}} p(x) \cdot dx \right|$$

  beside given uncertainty where A (mm^2) is the undeformed chip section, x (mm) is the location of profile point within a profile measuring range, p(x) (mm) is the fitted function, which describes the actual profile of the groove's bottom, x_{start} (mm) and x_{end} (mm) are the locations of the bottom's boundaries within the profile measuring range.
- **Equivalent undeformed chip thickness for a profile measurement can be determined by the following formula:**

  $$h_{eq} = \frac{A}{\left| x_{end} - x_{start} \right|}$$

  where h_{eq} (mm) is the equivalent undeformed chip thickness, A (mm^2) is the undeformed chip section, x_{start} (mm) és x_{end} (mm) are the locations of the bottom's boundaries within a profile measurement.
- **Based on the measured force data, value of the specific force of cutting (specified in the undeformed chip section) must be determined as function of h_{eq} equivalent undeformed chip thickness at a given angular position of the test part.**

My [B5] publication is related to Thesis 6.

ENGINEERING ARTWORK: Identification of sections and of boundaries of sections within the specific force model can be consistently and reproducibly accomplished for the realized face milling and face-grooving turning test by my unique and specially developed software suit, which was applied to the evaluation of current cutting tests as well.

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6. PUBLICATIONS RELATED TO THESIS POINTS

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