1st CIRP Conference on Surface Integrity (CSI)

Process Signatures – an Alternative Approach to Predicting Functional Workpiece Properties

E. Brinksmeier\textsuperscript{a}, R. Gläbe\textsuperscript{a*}, F. Klocke\textsuperscript{b}, D. A. Lucca\textsuperscript{c}

\textsuperscript{a} Laboratory for Precision Machining, University of Bremen, Badgasteiner Str. 2, 28359 Bremen, Germany
\textsuperscript{b} Werkzeugmaschinenlabor, RWTH Aachen, Steinbachstraße 19, 52074 Aachen, Germany
\textsuperscript{c} School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, OK 74078, USA

Abstract

The prediction of functional workpiece properties has attracted much interest in academia, as well as in industry over the last 50 years. Although considerable progress has been made for single, well-understood processes it is basically still not possible to predict surface and subsurface properties from known workpiece and machining parameters. This keynote paper aims at suggesting a solution to this problem by describing machining processes by their converted and dissipated energy in the workpiece material, significant process state variables and their generation dynamics. For this new approach the introduction of the term \textit{process signature} is suggested.

© 2012 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.

Selection and peer-review under responsibility of Prof. E. Brinksmeier

Keywords: Manufacturing process, Surface integrity, Energy, Process signature

1. Introduction

Every machining process causes several physical and chemical changes in the workpiece material. Mechanical, thermal and chemical effects influence the generation of the new surface, may activate dislocation movements, and change the material structure in the near surface including hardness, and residual stresses. Although these phenomena are basically of a different nature, they can all be traced back to a common basis of the converted and dissipated energy. This is the hypothesis of this keynote paper, and it is hoped that the following will lead to lively discussions on this topic.

It is well known, and has been proven many times, that the surface and subsurface properties have a considerable influence on the functional surface properties and thus on the functional performance of highly loaded parts [1]. This means that machining processes within their respective range of action can

\* Corresponding author. Tel.: +49-421-218-9434; fax: +49-421-218-9441.
E-mail address: glaebe@lfm.uni-bremen.de
influence the quality of a part favorably, as well as detrimentally. Against this background it has been the
target of many research projects and industrial efforts as well, to predict the functional workpiece
properties resulting from a given machining process. Although for individual cases remarkable results
have been achieved, it is still not possible to transfer process specific knowledge to other even similar
processes. A more general understanding as to how the workpiece material reacts to the physical and
chemical process impacts, and how this influences the functional workpiece properties, is still missing.
This is not only unsatisfactory but also amazing from a natural science point of view. Different machining
processes, even very different processes like cutting and laser beam machining can physically be reduced
to energy activated effects like mechanical deformation, temperature fields, and chemical reactions. This
takes us to the assumption that converted and dissipated energy in combination with the generation
dynamics of the process must be solely responsible for the resulting workpiece material modification. For
this new view on machining processes we would like to coin the term “process signature”. The process
signature aims to be a new energy-based approach to describe the interaction of a machining process with
a workpiece material. Such kind of process signatures have not yet been investigated nor do publications
report on this new fundamental approach. As a consequence, the development of process signatures
would require a lot of research effort. However, if the proposed way to describe processes from an energy
point of view would be successful, considerable potential in terms of material- and process efficiency
could be achieved. A pre-condition is, of course, that the interactions between a machining process and
the workpiece with its functionality are physically understood, can be described by conservation and state
variables, and can be represented by models. This paper will therefore introduce the general ideas for the
creation of process signatures.

2. State-of-the-art knowledge

The physical and chemical properties of surfaces and subsurface layers with respect to the functional
performance of a part can be summarized by the term surface integrity. This term was first coined by
Field and Kales in 1964 [2]. From then on, scientific discussion of functional properties and the
importance of manufacturing processes for these properties, and the resulting functional performance
received an increasing awareness. This has been proven for example by several CIRP papers and keynote
papers which received a lot of attention [3-5]. The importance of machining induced surface integrity was
also recognized by the German National Science Foundation (DFG) which realized a priority program on
manufacturing and functional performance of components in the early 1980’s [6]. About the same time,
the Institute for American National Standards released a surface integrity standard [7]. This industry-
driven standard listed more than 20 significant surface and subsurface properties which had a proven
influence on the functional performance of parts. The standard, however, was more or less a listing of
recognized important material properties and ways to measure them. A scientific-based understanding of
how workpiece modifications are generated by machining processes was not given. Also in the following
years the correlation of machining-induced process parameters and the resulting workpiece modifications
with respect to functional properties was only discussed in a few publications.

Much of the research work which was performed in the field of surface integrity relates to material
removal processes. A considerable number of publications is based on the very early work of Carslaw and
Jaeger who described the movement of a tool as a moving heat source [8]. It is the aim of this approach to
predict temperature fields in workpieces in order to describe thermal damage when a certain combination
of machining parameters are used. By this approach temperature-induced distortions of workpieces can be
predicted. Most of the work was focused on grinding processes; however cutting processes have also been
described by this approach. In combination with FEM programs the Jaeger-Carslaw solutions can also be
used to predict residual stresses. It can be stated in general that the use of advanced FEM software aids in understanding and predicting processes. A very good review on modelling and simulation of grinding processes was presented in the habilitation thesis of Heinzle, and a CIRP keynote paper from 2006 [9, 10]. The latest review on surface integrity and functional performance was presented in a CIRP keynote paper of Jawahir et al. from 2011 [1]. Interestingly this paper includes the results of a collaborative work which demonstrates clearly that the generation of residual stresses in a workpiece by an arbitrary process is still not possible. Obviously such targets can only be reached today in mass production after many preceding experiments. This provides evidence that manufacturing processes need to be described by more physics-based approaches. The proposed process signature may be a useful approach in that direction.

3. Generic development of process signatures

It is suggested here that a process signature will describe the individual peculiarities of different manufacturing processes and their interaction with the material in a unified way. As a result it is expected that this will be a reliable basis for the correlation of manufacturing processes with targeted functional workpiece properties. However, this aim can only be reached if the ordinary description of manufacturing processes (e.g., by the process parameters and material removal rates) will be extended or possibly even replaced by fundamental physical and chemical relationships. These relationships need to be known and have to be modelled on different scales in order to finally fuse them into a generic description for the process signature. This dictates that the material will be an integral part of the new description to be developed. Fig. 1 illustrates the basic elements of a process signature.

![Diagram of process signature](image)

*Fig. 1. Fundamental view of the key parameters of a process signature*

It becomes clear from Fig. 1 that the interaction time of processes with the material determines the exposure time for energy conversion and dissipation. This will, for example, determine the heat flow through the material surface layers including the spatial and time gradients. If the material’s reaction as a function of these impacts is known, conclusions for the functional performance of surfaces and surface layers can be drawn.
It should be pointed out here, that energy considerations of machining processes are not new. A very classical example is shown in Fig. 2. This view of a single grain impact in grinding has been developed by König in the early 1980’s and was modified by Klocke in 2005 [11,12]. It illustrates the energy dissipation as heat fluxes through the involved elements in the contact zone.

\[ q_{\text{total}} = q_{\text{lub}} + q_{\text{g}} + q_{\text{chip}} + q_{\text{w}} \]

Fig. 2. Schematic illustration of the energy conversion and the heat flow during a single grain impact in grinding

With the progress of process knowledge over the years, the availability of high resolution measuring equipment, the rapid development of computer capabilities, and thus the possibilities for extensive process modeling it should be possible today to describe the above mentioned actions in a more physical and thus in a more general way. The basic idea behind this hypothesis is to model the energy conversion and energy dissipation processes, which are dependent on the generation dynamics of the machining process and the material being machined. By doing this, pure physical parameters and conserved quantities could be used as model parameters.

4. Basic assumptions

The suggestion to develop process signatures is based on the fundamental assumption that all manufacturing processes are energy driven. Energy conversion and energy dissipation will impact fingerprints in the material and will thus determine the final surface and subsurface properties. From this observation it can be concluded that materials “don’t know processes”. They do solely react to the physical and chemical impacts resulting from the above mentioned energy flow. This view is schematically illustrated in Fig. 3 which compares a cutting process with a laser etching process. From an engineering point of view these processes are totally different. However, from a workpiece material’s point of view the physical and chemical actions along a causal sequence are basically very much comparable.

If it is agreed that machining processes always follow the same scheme we could derive an even more simplified and physically-based view of machining processes (Fig. 4).
Fig. 3. Causal sequence comprised of the energy conversion, energy dissipation, and material modification as a result of different machining processes.

Fig. 4. Physically-based view of machining processes.

The causal sequence would include the input parameters of a process, the major process actions, i.e., energy conversion, energy dissipation, and material modification, as well as knowledge of the output parameters, especially the functional properties. It is obvious that much research work is still needed to...
describe the interface layer between the input and the process, as well as the second interface layer between the process and the output quantities. Comparable to A/D-converters in the field of electronics we may designate the first interface layer as a technology/physics (T/P)-converter, and the second interface layer may be designated as a physics/technology (P/T)-converter.

The final goal of the development of process signatures would be to predict the functional properties and thus the functional performance of parts. If this was successful and if the causal sequence can be described precise enough, the 'inverse problem’ could also be solved. This means that for defined functional properties different processes and process sequences might be chosen to generate exactly the desired properties. Therefore, a final view of the process signature would include the functional performance of parts. This is schematically shown in Fig. 5.

5. Examples giving evidence for the existence of process signatures

The preceding suggestions conclude that the use of conserved quantities for a physical description of manufacturing processes may basically be feasible. The following examples give evidence for the importance of energy and further physical quantities in selected machining processes.

For different grinding processes Fig. 6 shows schematically the surface residual stresses of the workpiece as a function of the specific grinding power. This schematic diagram has been constructed from many substantial experimental investigations. Basically the residual stresses are a function of the converted and dissipated energy in the surface layers and the resulting temperature gradients.

The figure shows that a targeted residual stress value can be achieved by different means. Let us assume that we start on a certain point on the curve of process 3. Following root 1 we could achieve the targeted residual compressive stresses by reducing the specific grinding power. This however would be accompanied by a reduction of the process productivity. Root 2 is an alternative approach. Here, we jump onto the curve of process 4 which, for example, uses CBN grinding wheels instead of aluminum oxide wheels. The dominant quantity governing the residual stress state is obviously the dissipated heat per unit area of the contact zone. It would be desirable that this heat flow is predicted by the process signature.
Another example is taken from investigations into grind hardening (cf. Fig. 7). This process is characterized by many physical quantities and quite complex interactions of the process with the material. Despite this it is possible to predict the working result (successful surface layer hardening) by knowing the surface-related process energy.

![Graph showing residual surface stresses versus the specific process power for different grinding processes](image)

**Fig.6.** Residual surface stresses versus the specific process power for different grinding processes [13]

| evaluation criteria | surface hardness | hardening depth \( h d \) respectively depth \( z \) of the heat-affected zone |
|---------------------|------------------|------------------------------------------------------------------|
| „good“              | ≥ 55             | ≥ 0.5 mm                                                         |
| „medium”            | ≥ 40             | ≥ 0.2 mm                                                         |
| „bad“               | < 40             | < 0.2 mm                                                         |

\[
\frac{P_c''}{W/\text{mm}^2} = \left( \frac{\Delta t}{s} \right)^{0.25 \pm 0.13} = 74 \pm 4
\]

![Graph showing identification of successful grind hardening results by using physical process parameters](image)

**Fig.7.** Identification of successful grind hardening results by using physical process parameters [9]
It is obvious that the process dynamics represented by the heat exposure time has a decisive influence on the result also. The plotted surface-related energy was calculated from the specific grinding power and the heat exposure time. The generation of this graph is also based on substantial experimental investigations. If process signatures were available it is possible that such results may be predicted by much less experimental effort.

The fact that a material ‘does not know processes’ is shown in Fig. 8. The figure shows that qualitatively comparable surface and subsurface properties can be achieved by fundamentally different machining processes. The major physical impacts on the material (thermal, mechanical) are basically different. It would be a major step in manufacturing science if process signatures could be identified, such that a description of the effects could be achieved in a unified way.

- different processes: similar surface layer properties
- workpiece material: does not know processes
- material reacts to thermal and mechanical exposure, resulting from the energy conversion and dissipation, and the generating dynamics of the process

Fig.8. Examples for the observation that different processes can lead to similar surface and subsurface properties

6. Conclusions

It has been suggested that establishing a process signature can serve as a universal description for machining processes. This description takes into account the interaction between the process and the material for predicting the functional properties of the surface and subsurface layers. The process signature is based on the converted and dissipated energy of the process.

In current research, energy is frequently used to correlate processes with the functional properties which result. Energy can also be used to show similarities between processes. However, despite the fact that all machining processes have similarities, there is no general approach for describing them in a unified way. A process signature may also be useful for predicting suitable machining processes to
achieve specific functional properties. Achieving specific functionality will be particularly relevant for industrial processes.

The development of a process signature requires highly interdisciplinary research including machining technologies, materials characterization and modeling, as well as novel approaches for descriptive methods, a challenging task for future research.

References

[1] Jawahir I S, Brinksmeier E, M’Saoubi R, Aspinwall D K, Outeiro JC, Meyer D, Umbrello D; Jayal A D. Surface Integrity in Material Removal Processes. Recent Advances. Annals of the CIRP 60/2; 2011: 603-626.

[2] Field M, Kahles JF. The surface integrity of machined and high strength steels. DMIC Report, 210; 1964: 54-77.

[3] Tönshoff H K, Brinksmeier, E. Determination of the Mechanical and Thermal Influences on Machined Surfaces by Microhardness and Residual Stress Analysis. Annals of the CIRP 29/2; 1980: 519-530.

[4] Brinksmeier E. X-Ray Stress Measurement - A Tool for the Study and Layout of Machining Processes. Annals of the CIRP 34/1; 1985: 485-490.

[5] Lucca DA, Brinksmeier E, Goch G. Progress in Assessing Surface and Subsurface integrity. Annals of the CIRP 47/2;1998: 669-693.

[6] German National Science Foundation/ priority program. Fertigung und Bauteilverhalten. Deutscher Verband für Materialprüfung: DVM-Tag 1983; Düsseldorf; 1983.

[7] American National Standard. Surface Integrity. ANSI B211.1-1986. American National Standard Institute, New York; 1986.

[8] Carslaw H, Jaeger J C. Conduction of heat in solids. Oxford Science Publications, Oxford University Press; 1959: 510-594.

[9] Heinzel C. Schleifprozesse verstehen: Zum Stand der Modellbildung und Simulation sowie unterstützender Methoden. Habilitation; University Bremen; Shaker; 2009.

[10] Brinksmeier E. et al. Advances in Modelling and Simulation of Grinding processes. CIRP Annals; 55/2/2006; 667-696.

[11] König W. Fertigungsverfahren. Part 2 VDI-Verlag; 1980.

[12] König W, Klocke F. Fertigungstechnik. Part 2 VDI-Verlag; 2005.

[13] Brinksmeier E. Prozess- und Werkstückqualität in der Feinbearbeitung. Habilitationsschrift; University Hannover; VDI Verlag; Fortschritts-Berichte VDI Series 2 Nr. 234; Düsseldorf; 1991.