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Design methodology for hybrid production processes

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Abstract

Current developments of hybrid production processes or production systems exceed the performance in manufacturing. Most of these developments have in common that they have mainly been found intuitively. Up to now the development of new hybrid production systems leads to high amounts of operative planning. The challenge is to develop a systematic and scientific approach for aggregating, describing, explaining and combining single processes. This paper introduces a systematic approach of the design methodology for developing hybrid production processes. In terms of identifying hybrid process solutions as part of an innovation process, the applicability of different TRIZ tools is shown concerning the specific requirements of manufacturing processes development.

Keywords: TRIZ; Hybrid processes; Hybrid production; Manufacturing processes; Grinding; Grind-hardening;

1. Introduction

The manufacture of innovative products often fails due to technological limitations of today's production systems and processes. The hybridisation of manufacturing processes can help to break the limits of today's production systems and to realise innovative products. Thus developments of new hybrid manufacturing technologies arouse high expectations.

Previous developments of hybrid machining processes mostly base on intuitively or randomly found solutions. As yet a methodology for the systematic development of hybrid machining technologies does not exist. But as known from other scientific disciplines, a big part of solutions can not be found effectively without a methodological approach [1] [2] [3] [4]. Hence it can be assumed, that up to now the full potential of hybrid technologies is not exploited by far.

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2. Hybrid production processes

2.1. Ontology of hybrid production processes

Within hybrid production processes different forms of energy or forms of energy caused on different ways respectively are used at the same time at the same zone of impact. Hybrid production processes are also defined as the combination of effects that are conventionally caused by separated processes in one single process at the same time [5].

The realisation of hybrid production processes bases on two approaches. By the integration of specific forms of energy in the work area of the process the machinability of the workpiece material is improved or the process mechanisms as well as the process characteristics are improved itself.

For the realisation of these approaches, one or more supplementary forms of energy have to be coupled into the existing process. For this purpose several different forms of energy combinations are possible consisting of e.g. thermal, mechanical or chemical energy, although the technological advantage and the possibilities of realisation must be considered [6].

2.2. Potentials of hybrid production processes

For the majority of companies in production industry – especially in high wage countries – innovation is one of the most important factors of success. Concerning this matter it is not only the product idea that contributes to a higher success, but also the capability of optimal production processes. In this context optimal means most efficient, flexible and stable at the same time. Broad manufacturing process know-how is necessary to run a technology near its limits of performance. However the full use of today’s manufacturing technologies by means of conventional optimisation in most cases does not lead to a leap of performance. Hybridisation of conventional technologies is a way of reaching new technology capabilities in production systems.

Figure 1 shows how hybrid processes can improve a production in terms of process chain shortening or the realisation of new product qualities.

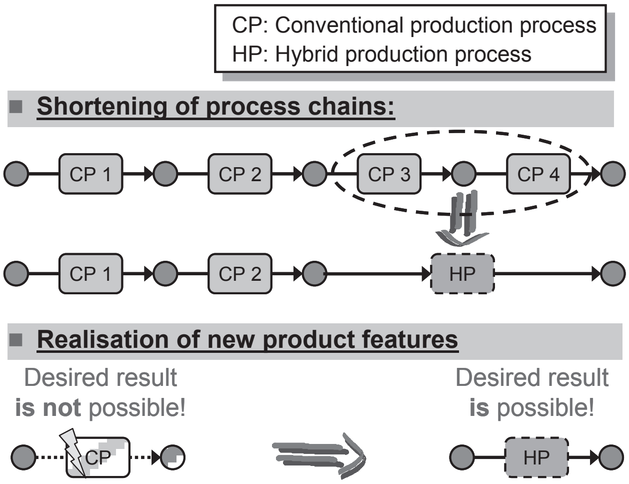


Figure 1: Aims of hybrid production processes

By the described technology integrations the process chain can be shortened due to the substitution of several processes by a single hybrid process. Further this can lead to a reduction of planning operations that are necessary to synchronise several processes in a process chain, even though a hybrid process may be more complex and may cause more requirements concerning process stability. Nevertheless a second aim of developing hybrid processes is to realise new product qualities. For example by hybridisation a conventional process can be enabled to machine new materials that according to the state of the art could not be machined by the conventional process yet. Based on these new production capabilities innovative products could be realised, that could not be produced (economically) due to the technological limitations of today's production technologies.

3. Methodology development

The research and development of production technologies often focuses on single production processes concerning specific applications. This profound research is very specialised and vital for the understanding of the mechanisms of known production processes. The knowledge about the mechanisms of single technologies enables these production processes to be adapted and optimised for a wide field of specific product requirements. According to the s-curve theory the possibility of process improvement decreases after a specific time considering single processes respectively – in this state the technology is optimised near to its limits. In the case of conventional, widely investigated manufacturing technologies, production research often focuses on adapting the known technologies for new applications such as the machining of new workpiece materials. On the other side more capable and efficient manufacturing technologies have to be developed. Assuming that the possibilities of hybrid production technologies is not utilised by far, the development of new inventive production technologies has to consider and combine the mechanisms of different single processes. For this purpose the integration of profound process knowledge from different production technology disciplines is necessary. In order to provide the broad field of necessary knowledge, it has to be compressed in an abstract way to get new ideas, which is the first step of inventive solutions.

The aim of the herein described scientific work is to develop a systematic tool for:

- optimisation of technology chains based on technology profiles
- describing and explaining of technology limits
- generating inventive solutions e.g. in terms of hybrid production technologies

TRIZ and the steps of hybrid production process design

To find inventive (hybrid) process solutions, different steps have to be proceeded.

Figure 2 shows a general structure of the methodology and its similarities to the general TRIZ algorithm.

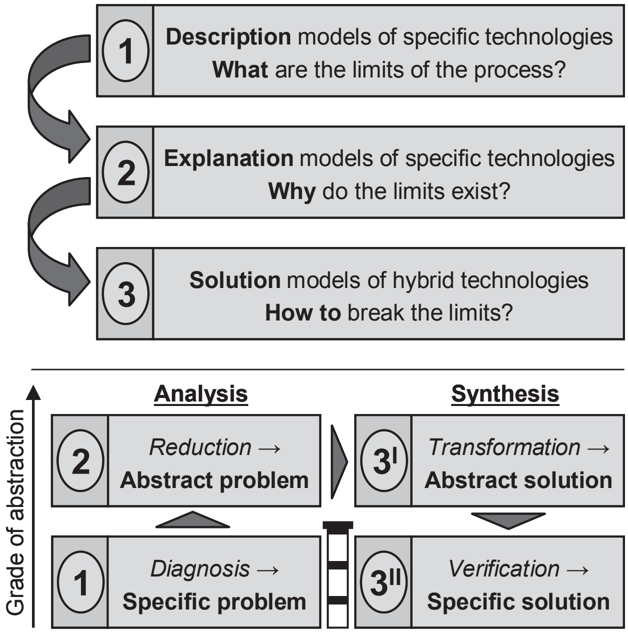


Figure 2: Steps of the design methodology for production processes and similarities to general TRIZ algorithm

The herein presented approach bases on the assumption, that a new process solution only can be developed if the limits of a technology are known as well as their reasons and that they can be described. The limits of technologies can be characterised in terms of problems, while a problem is defined as a contradiction. Thus in the first steps of the methodology the problems of today's technologies must be analysed systematically. TRIZ provides several methodological tools for the purpose of analysing problems. In accordance with the TRIZ methodology the technology limits are described in terms of standard problems through abstract physical or technical contradictions. By means of TRIZ, standard solutions can be identified for standard problems (e.g. by contradiction matrix, separation principles, standard solutions for substance field models) [7] [8] [9] [10].

Based on an aggregation of solutions and mechanisms of known production processes – single and hybrid processes as well – analogies can be provided to support the search for a specific solution. E.g. if a local heating of the work piece surface layer is required the use of laser beams is a specific solution as it is known from laser-supported turning or laser-supported incremental sheet metal forming.

3.1. Description level – Identification of limits

Technology capabilities can be described by several criteria composed of output quantities or output characteristics, which are related to the resulting workpiece, the tool wear or the productivity, see Figure 3. While the tool wear and the productivity primarily are economical evaluation criteria, the workpiece results are technological criteria.

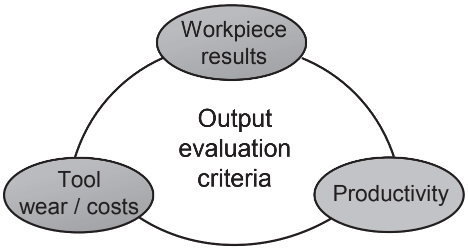


Figure 3: Evaluation criteria of a manufacturing process

The single manufacturing process can be described in terms of a black box by its input and output parameters, see Figure 4. This kind of description model reduces the complexity of a manufacturing process. In manufacturing research the correlations between input and output parameters of a specific process are often described by empiric-analytical models, which are based on experimental investigations. The results of these investigations are used for the purpose of process chain generation. In a process chain the workpiece state output of one single process is the workpiece state input of the following process until the desired workpiece condition is reached.

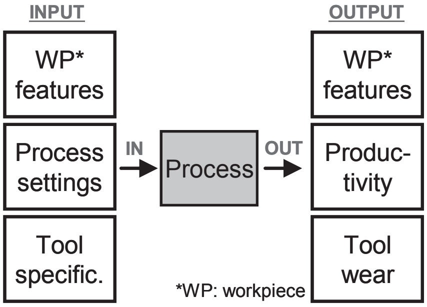


Figure 4: Black box model of a production process

The description of the workpiece state before and after the manufacturing process classifies the workpiece characteristics into macro geometry, surface topography, surface layer and bulk features. In the first procedures of the herein introduced methodology a technology is described concerning the results of workpiece surface topography and the influence on the workpiece material characteristics. For this purpose a workpiece element is defined. The difference between the states of the workpiece element before and after a manufacturing process describes the manipulation of the workpiece by the process. Hence, for the use of process chain generation the considered technology is sufficiently described by the change of the workpiece element characteristics.

Figure 5 shows an example of a workpiece influenced by a grinding process. The surface layer consists of a re-hardening zone and an annealing zone. This manipulation is also known as “grinding burn”.

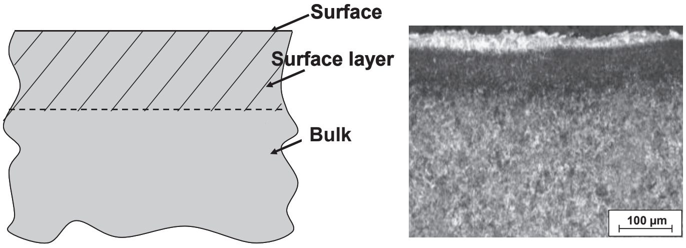
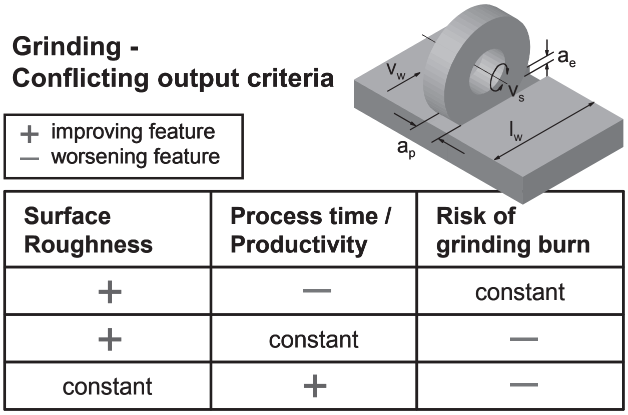


Figure 5: Workpiece model and surface layer analysis micrograph of a ground workpiece

In general, technological limits derive from a matching of required product results and technology capabilities. The realisation of some requirements is often directly opposed. The better the one criterion the worse gets the other one. In most technologies characteristic conflicting process output criteria are e.g. accuracy and productivity or tool wear and productivity. The below example of a conventional grinding process illustrates the above described context.

In the below example the assumed object is to optimise a conventional grinding process. A capability profile of the grinding process shows the following relation tendencies between some important output parameters of a grinding process:



Surface Roughness	Process time / Productivity	Risk of grinding burn
+	—	constant
+	constant	—
constant	+	—

Figure 6: Characteristic conflicting output criteria of a grinding process

If the surface roughness of the grinding process should be improved e.g. the infeed speed can be reduced, which causes longer process times and thus leads to a lower productivity. If the productivity should be constant, the surface roughness can be improved e.g. by a higher cutting speed or by the use of another grinding wheel specification that features a lower grain size. Both lead to a higher risk of grinding burn.

As shown in the above example undesirable process outputs and generally conflicting outputs are aggregated for many different manufacturing technologies. This is the basic for a broad description of limits in production technologies.

3.2. Interpretation level – Reasons for limits

While the above described first step of the methodology features a phenomenological/descriptive view, in the following step the interrelationships of the process are considered by means of causes and effects. The change of view from the phenomenological to an interpretational view is also expressed by the terms that are used within the process models. Within the description level the terms of input and output mainly have been used. Within the interpretation level technology outputs are understood as effects at the end of a cause-and-effect chain. Hence, the production process is no longer described as a black box, but it is characterised by a cause-and-effect chain as shown in

Figure 7.

Compared to the descriptive process model in

Figure 4 the process is divided into two sub-models. The first sub-model *"Interaction" is technology specific*. It represents the mechanisms of interaction between the production system elements such as the interactions between tool and workpiece. Within these interactions energies are transmuted. E.g. the kinematic energy of a moving tool or workpiece are transmuted into work of friction and deformation, thus lead to mechanical and thermal energy as an effect of the interaction. The effected energies are defined as process characteristics. As a function of place and time these process characteristics describes the production process in a technology unspecific way without the need of profound information about the process input parameters. The technology unspecific process characteristics are vital for a common semantic for the purpose of comparing and combining different technologies.

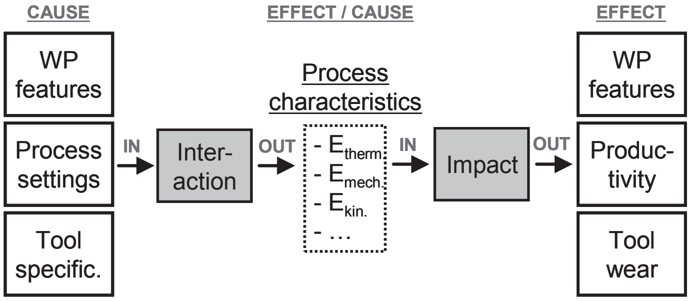


Figure 7: General interpretation model of a manufacturing process

In opposite to the sub-model "Interaction", the second sub-model *"Impact" is technology unspecific*. It represents the impact of the process characteristics on the process results such as the workpiece features and the tool wear. Within this sub-model the process characteristics are the root causes of the results.

It has to be remarked that

Figure 7 shows a reduced model in order to clarify the idea of the model. In case of applying to a specific technology problem, it can be adapted or added by further cause and effect elements. E.g. the influence of specific machine specifications, supplies such as lubricants and external disturbances is not considered. Also the feedback of tool wear is neglected in this model, because in this case it is presumed that the principles of physical mechanisms do not change while tool wear appears.

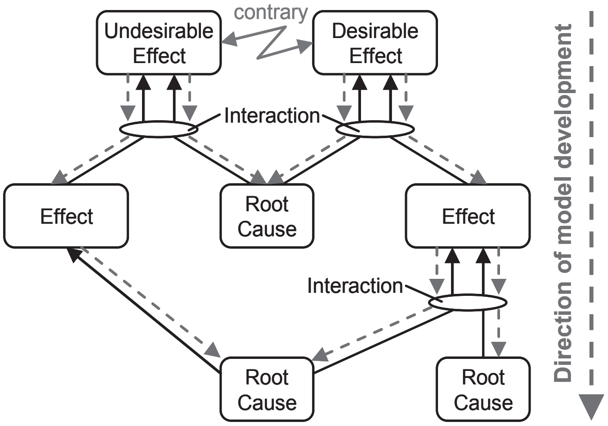


Figure 8: General model of cause-and-effect relations according to the Theory of Constraints [11]

In order to improve the technology by means of major changes of the manufacturing system instead of optimising the existing system by a compromise between process settings, the undesirable process results have to be traced back to their physical mechanisms and root causes. The cause-and-effect chains of specific undesirable effects such as high tool wear or subsurface damages of the workpiece can be described according to the "Theory of Constraint (TOC)" [11], see

Figure 8. The construction of this model emanates from the undesirable and desirable effects that represent the contrary output criteria of the considered technology. The advantage of this diagram is the transparency of the cause-and-effect relationships. In many cases the real root causes are not identified. Instead of this the system is tried to improve by changing parameters that do not have a main impact on the undesired result or parameters that are effects of the real root causes itself. Additional by means of weighting the cause-and-effect relationships it is possible to identify the core problem, which features the main impact on the undesired effect.

3.3. Design level – breaking the limits

Today's manufacturing technology research and development often focuses on the optimisation of single processes for specific applications by means of changing the tool specification and process setting parameters. This kind of process improvement is represented by the conventional optimisation approaches, see upper part of

Figure 9. The *need for radical changes* of technologies cannot be achieved by these approaches.

Though the mechanisms of single technologies today are profoundly investigated and modelled in detail by several experts, interdisciplinary solutions are found rarely. The reasons are the limited individual knowledge concerning other disciplines or technologies respectively as well as psychological barriers (psychological inertia vector). In order to increase the probability of interdisciplinary solutions in production technology research and development a link of different technology models is vital. As mentioned above the technology unspecific process characteristics are used in this approach as a common semantic and interface respectively for different technology models.

After applying and executing all conventional optimisation approaches, the lower part of

Figure 9 illustrates another way in order to achieve a radical improvement in terms of clearly enhancing the technical limits of a known process.

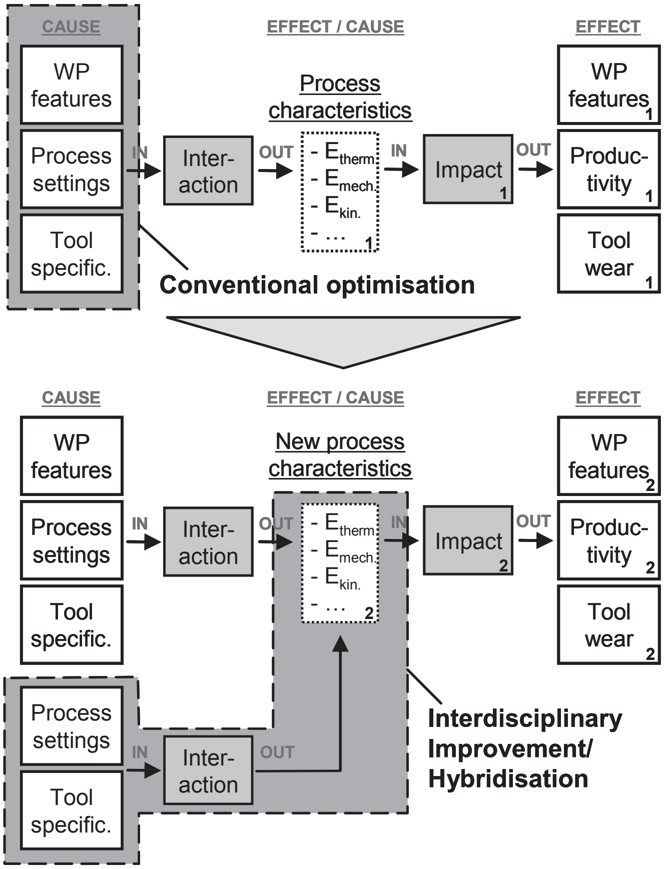


Figure 9: Illustration of conventional optimisation vs. interdisciplinary improvement of production processes

Assuming the possibilities of conventional optimisation is nearly exploited; the process can only be improved by changing the composition of process characteristics by external (energy) sources. This integration is based on an interaction of the added technology and the workpiece or the conventional process as well.

Another possibility of finding hybrid solution is to analyse the resources of process chains in terms of cause-and-effect relations. Based on this, a process chain may be improved by integrating single processes or the impacts of several processes respectively in one technology.

The above described design level of the methodology provides a way to find hybrid production technology solution. The general structure of this approach is based on the principles of TRIZ. Furthermore several tools of the TRIZ methodology have to be integrated to the introduced procedure in order to provide an effective applicable way that can extend the capabilities of technology development in production research.

4. Integration of production process design and TRIZ

The basic correspondences between TRIZ and the steps of hybrid production process design have been shown above, see

Figure 2. The parallels between TRIZ and the introduced production process design methodology show a high potential for the use of TRIZ within this context. The main parallels are shown in the following [7] [8] [9] [10].

Interdisciplinary solutions

For the purpose of finding hybrid solutions the combination of different technology models is necessary. Due to the psychological inertia vector (PIV) the non-methodological problem solving process mostly focuses on a small field of possible solutions, which is limited to the technological knowledge of the individual person. An interdisciplinary solution often is outside of the focus of solution that is determined by the PIV. Such an inventive solution has to be found systematically, e.g. supported by several TRIZ tools.

The ideal solution

Both TRIZ and the hybrid production process design methodology aim at the "ideal solution" instead of accepting early compromises. In order to achieve a technology improvement with higher ideality compared to conventional optimisation, at least two conflicting output criteria of the manufacturing system have to be improved at the same time.

Analogies

The analogy approach bases on the assumption, that most problems already have been solved in other disciplines or another context respectively. Hence, new solutions often can be found based on analogue solution principles that have been realised in other technical areas. This implies an aggregation of known solution and an extracting of solution principles. In the field of manufacturing technologies, existing technology database systems can help to analyse existing solutions in order to find solutions for unsolved problem. In terms of an efficient production process design methodology technology only limited knowledge can be given und thus must be provided purposeful.

Abstraction

Known specific solutions can be used to identify standard solution strategies, that can be used to find a solution for another specific problem. The linking of solution and problem is enabled by an abstract modelling of the specific problem. This origin idea of TRIZ is followed by the herein introduced modelling of single processes. The problem of a technology is described in an abstract manner by process characteristics based on their physical mechanisms. In a next step the solutions are generated on this abstraction level as described in Chapter 3.3.

In literature TRIZ is described as a methodology, consisting of different method tools.

Figure 10 summarises several TRIZ tools as they are used for problem solving in a broad field of applications.

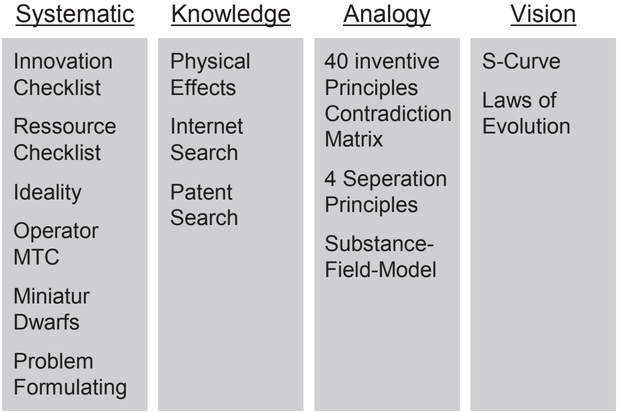


Figure 10: TRIZ tools overview [12]

Concerning the integration of TRIZ and the introduced methodology of production process design, the applicability of several TRIZ tools is evaluated by means of known hybrid production processes. Hereby the physical mechanisms of single processes are considered and process solutions are developed by the help of TRIZ tools respectively.

In the following the application of the above described methodology in combination with several TRIZ tools is exemplified by the technology evolution from grinding to grind-hardening as a new hybrid application of the grinding process.

4.1. Grind-hardening

Grinding is generally used as a finishing process of hard materials due to its high dimensional and shape accuracy, although grinding can be used for high stock removal rates as well.

Identification of limits in grinding

In grinding of hardened steel, undesirable effects can appear near to the ground surface such as crack formation, workpiece material structure transformation, modification of hardness progression, and residual tensile stress. As mentioned in chapter 3.1 the workpiece material structure transmutations – also called grinding burn - can be divided in a white etching re-hardening zone and an annealing zone, see

Figure 5. The annealing zone features a lower hardness than the bulk material. The re-hardening layer is harder and more brittle compared to the bulk material. The generally conflicting output criteria of a grinding process concerning grinding burn have been shown in

Figure 6.

Reasons for limits of grinding

The progression of temperature over the time is the main influence factor of dimension and modality of the surface layer. The temperature progression can be characterised e.g. by the maximum temperature and time period of thermal impact [13].

Figure 11 shows the cause-and-effect relationship of the grinding process regarding the above mentioned undesirable effect of grinding burn, that occur if the productivity is raised to a critical point, while the surface roughness and tool wear is constant.

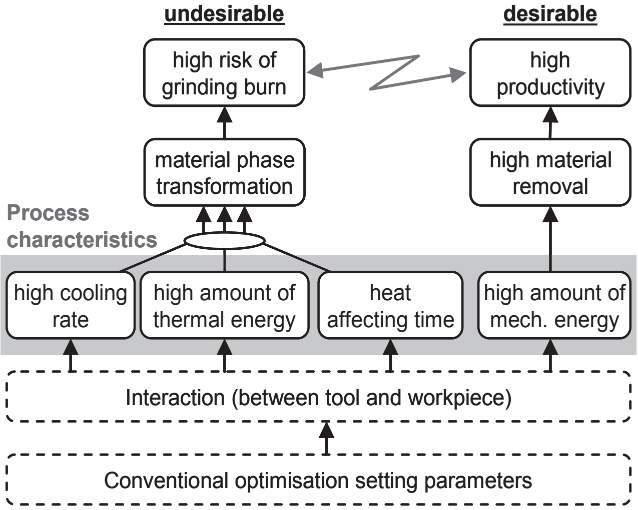


Figure 11: Cause-and-effect model of a grinding process

It is assumed, that all conventional optimisation approaches according to

Figure 9 are exhausted, so that the root causes in terms off setting parameters are not considered in

Figure 11. In a first step it is also sufficient not to regard the interaction of tool and workpiece. Instead the first object of process improvement is the level of process characteristics, which are assumed to result from the process interactions. In opposite to the other system and process setting parameters, the initial workpiece material features have turned out to be important information, which has to be considered on every abstraction level of the process model. It is a crucial fact that the effects of interaction as well as the effects of process impact, such as material structure transmutations, depend on the initial material state in a great extent.

Breaking the limits of grinding

In order to find a solution for the above described problem in terms of TRIZ, the first step is to define the problem in form of a contradiction. In

Figure 12 the reduced substance field model of the grinding process depicts the problem.

Between the grinding wheel and the workpiece a mechanical field is generated effecting the desirable chip formation and thus the material removal. A thermal field is generated as a second field that causes the undesirable effect of thermal workpiece surface damages.

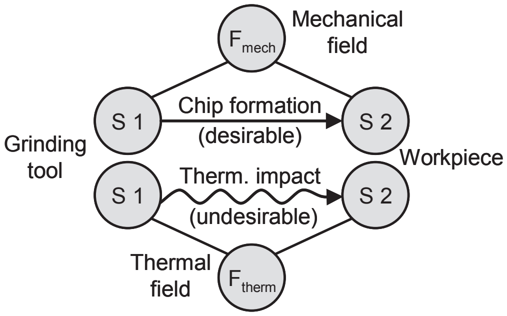


Figure 12: Reduced substance field model of a grinding process

Due to physical laws in conventional grinding the amounts of thermal and mechanical energy are correlated, both are affected by the total amount of process energy. The use of standard solutions has brought out some known solutions such as using cooling lubricants. Cooling lubricants can improve the ratio between the mechanical and the thermal fields. Up to now no other solution was found to resolve this relation. Thus the problem can be described by a *physical contradiction*:

- Process energy must be high.
- Process energy must be low.

A possible solution is to apply the principle of separation in time. While in a rough machining process the productivity is high, a damaged surface layer can be compensated by a finishing process afterwards. This solution is well known and probably the most applied one in industry, but it is not a hybrid process solution. To find another solution for this particular problem is a big challenge for future research.

Another approach is to change the view of examination to the *superior system* of process chains. As long as there is no specific application to be considered, it is appropriate to describe a process chain, which is commonly linked to grinding technologies. Grinding is mostly used for hard machining and thus the grinding process very often follows a heat treatment process. Here the heat treatment is applied in order to harden the surface layer. Hence, the considered process chain consists of soft machining, followed by heat treatment (e.g. induction hardening or laser hardening), and followed by grinding for hard machining. The heat treatment processes cannot easily be integrated into the production line. For this reason the heat treatment process involves some more processes due to transport and cleaning operations that are time and cost consuming, see

Figure 13.

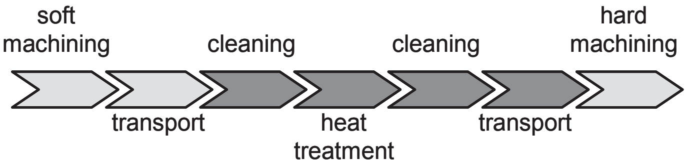


Figure 13: Conventional process chain commonly linked to a grinding process

By an expansion of the above shown cause-and-effect description to the process chain, the TRIZ tools “Innovation Checklist” (ICL) and “Resource Checklist” (RCL) respectively can be used. In terms of this process design methodology not the technologies but their abstract cause-and-effect relationships are considered as the resources of a process chain. Within the considered process chain an accumulation and comparison of cause-and-effect models of all participating technologies shows a common cause-and-effect relationship shared by the grinding and hardening process as shown in

Figure 14.

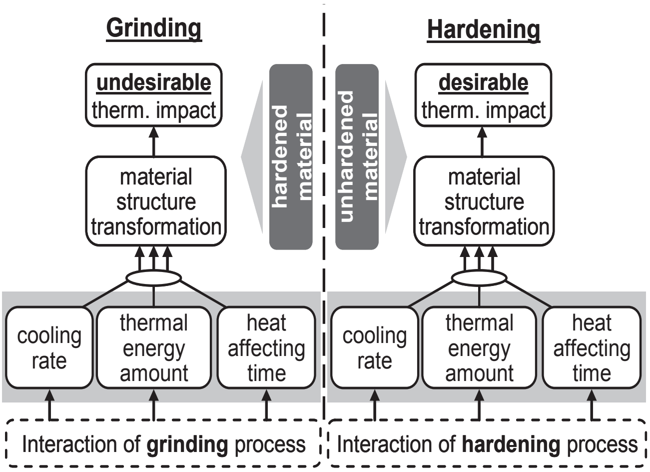


Figure 14: Common cause and effect relationship shared by grinding and hardening processes

Concerning the thermal aspects of the processes the same process characteristics determine the thermal impact onto the workpiece surface layer. While the effect of material structure transformation in grinding leads to undesired grinding burn, the material structure transformation in hardening causes the desired process result. The crucial difference between the two technologies is that the initial state of workpiece material of a grinding process is a hardened material, but in hardening the material is unhardened before. Using the principles of ICL/RCL it can be concluded, that grinding of hardened material can lead to undesired grinding burn, but in grinding of unhardened materials it may be possible to use the heat progression for the purpose of surface hardening [14].

Figure 15 shows the principle of grind-hardening.

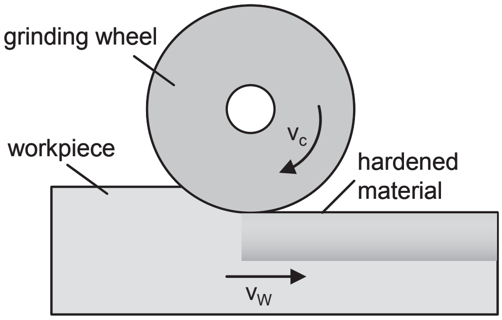


Figure 15: Principle of grind-hardening

As primary experimental investigations already has shown, the heat generated in grinding can be utilised for thermal induced surface hardening effect up to mm-scale. They have shown that the metallurgical effects in grind-hardening are comparable to those of conventional surface hardening technologies such as laser and induction hardening [14] [15] [16] [17] [18].

By the use of grind-hardening a separate hardening process can be substituted and therewith involved time and cost consuming transport and cleaning processes get unnecessary, see

Figure 16.

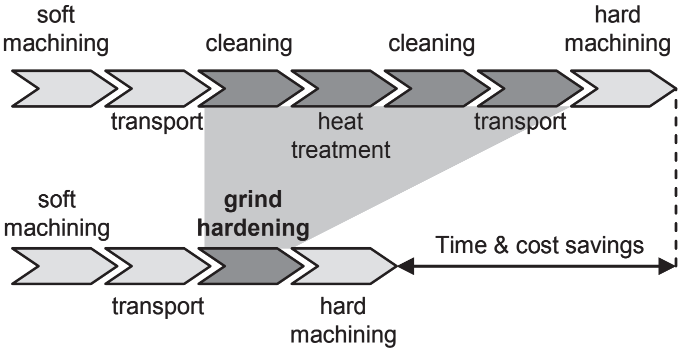


Figure 16: Shortening of process chain by grind-hardening

Thus a new application of grinding technology was found in using the thermal source of a grinding process for surface material hardening.

5. Summary

This paper introduced a systematic approach of a design methodology for developing hybrid production processes that can clearly enhance the capability limits of today's production technology systems. According to the principles of TRIZ the herein introduced approach consists of three steps. First generally technology capability limitations (problems) have to be found in terms of contradictions. Secondly specific limits must be traced back to its physical causes by exploring cause-and-effect relations. A technology unspecific description of the process characteristics is used to find abstract solutions. These abstract solutions are the origin for the integration of different technologies and thus for new approaches in terms of breaking the limitations of single technologies by radical changes. TRIZ provides several method tools that support the search for inventive (hybrid) production process solutions and that have to be integrated respectively.

As illustrated in the use case of grind-hardening the introduced systematic approach supports the technology development in terms of generating new ideas and solutions for enhancing the limits of today's production technologies.

Acknowledgments

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References

[1] Altschuller, G.: „Erfinden – Wege zur Lösung technischer Probleme“. (Ed.): Thiel, R; Patzwaldt, Berlin: Verlag Technik, 1984

[2] Klein, B.: „TRIZ/TIPS – Methodik des erfinderischen Problemlösens“. München: Oldenbourg Wissenschaftsverlag, 2002, ISBN 3-486-58083-3

[3] Orloff, M. A.:, 2002: „Grundlagen der klassischen TRIZ – Ein praktisches Lehrbuch des erfinderischen Denkens für Ingenieure“. Berlin: Springer-Verlag, 2002, ISBN 3-540-66869-1

[4] Zobel, D.: „TRIZ für Alle“. Renningen: expert Verlag, 2006, ISBN 3-8169-2396-8

[5] Feinauer, A. et al.: „Werkzeugmaschinen für die Produktion von morgen im Spannungsfeld: flexibel und einfach, schnell und genau.“ In: Eversheim, W. et al. (Ed.): Wettbewerbsfaktor Produktionstechnik. Aachener Werkzeugmaschinen Kolloquium 2005. Aachen: Shaker, 2005, pp. 373-409

[6] Eversheim, W.; Klocke, F.; Pfeifer, T.; Weck, M. (Ed.): „Hybride Prozesse – Neue Wege zu anspruchsvollen Produkten.“ In: Aachener Werkzeugmaschinen Kolloquium. Wettbewerbsfaktor Produktionstechnik. Aachener Perspektiven. Aachen: Shaker, 1999, pp. 243-278

[7] Orloff, M. A.: “Inventive Thinking Through TRIZ: A Practical Introduction”. 1st Ed., New York: Springer-Verlag. 2003, ISBN 3540440186

[8] Altshuller, G.: “The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity.” Worchester, Massachusetts: Technical Innovation Center. 1999, ISBN 0964074044

[9] Altshuller, G.: “And Suddenly the Invenor Appeared: TRIZ, the Theory of Inventive Problem Solving.” Worchester, Massachusetts: Technical Innovation Center. 1996, ISBN 0-9640740-2-8

[10] Altshuller, G.: “40 Principles: Triz Keys to Technical Innovation.” Worchester, Massachusetts: Technical Innovation Center. 2002, ISBN 0964074036

[11] Dettmer, H. W.: “Goldratt’s Theory of Constraints – A Systems Approach to Continuous Improvement.” Quality Press, 1997, ISBN 0-87389-370-0

[12] Jantschgi, J; Shub, L.: „TRIZ – Innovativer Irrgarten der Werkzeuge“, In: Gundlach C. et al: Innovation mit TRIZ – Konzepte, Werkzeuge, Praxisan-wendungen. Düsseldorf: Symposion, 2006, pp. 59 – 73, ISBN 3-936608-74-1

[13] Nachmani, Z.: “Randzonenbeeinflussung beim Schnellhubschleifen”, Dissertation at RWTH Aachen University, Aachen: Apprimus Verlag, 2008, ISBN 978-3-940565-07-5

[14] Brinksmeier, E.; Brockhoff, T.: „Advanced Grinding Processes for Surface Strengthening of Struktural Parts“, In: Machining Science and Technology, Volume 1, Issue 2, pp. 299 – 309, Taylor & Francis, 1997, ISSN 1091-0344

[15] Brockhoff, T.: “Surface Hardening by Using Advanced, Grinding, Technology”, In: Abrasives Magazine, December/January 1997/98, pp. 10 - 11 and 32 – 37

[16] Brockhoff, T.: “Grind-Hardening: A Comprehensive View”, Annals of the CIRP Vol. 48, Nr. 1, pp. 255 – 260, 1999, ISSN 0007-8506

[17] Brockhoff, T.: „Schleifprozesse zur martensitischen Randschichthärtung von Stählen“, Dissertation at University of Bremen, Aachen: Shaker Verlag, 1998, ISBN 3-8265-6020-5

[18] Stör, R.: „Untersuchung und Entwicklung des Innenrundschleifhärtens“, Dissertation at University of Bremen, Aachen: Shaker Verlag, 2008, ISBN 978-3-8322-7107-7

[19] www.production-research.de