Transferring life cycle engineering to surface engineering

Alexander Leiden, Peter-Jochen Brand, Felipe Cerdas, Sebastian Thiede, Christoph Herrmann

Abstract

Most surface finishing processes for metals are associated with a high energy demand and the use of chemicals with the potential impact on human- and eco-toxicity. However, surface finishing processes can lead to environmental and economic benefits in other life cycle phases by reducing friction, wear and corrosion.

The application of life cycle engineering into surface engineering allows to understand these effects. This study provides a framework to assess environmental and economic effects of surface treatments on other life cycle phases. A case study illustrates the contribution of a surface finishing process for cutting inserts to the life cycle performance.

1. Introduction

Corrosion, friction and wear of components surfaces cause a significant environmental and economic impact directly and indirectly in all relevant industry, infrastructure and transport sectors (NACE - National Association of Corrosion Engineers, 2019). As summary of studies from the last decades, the corrosion costs can be estimated as 3-4% of the gross domestic product of a country per year (Koch, 2017). Corrosion also causes relevant direct and indirect environmental impacts (Hansson, 2011). For example, corrosion products from metals are emitted directly to the local environment and corruptions indirectly lead to inefficiencies and system failures. Wear and friction are responsible for 1-2% losses of the gross domestic product per year and up to 10.9% of the primary energy demand through system in efficiencies (Woydt et al., 2019). Especially in the mining and metal working industry high losses occur due to the use of cutting materials.

To tackle these issues in the use stage of products, surface treatment processes are applied to most corrosion and wear sensitive materials in all sectors as part of the manufacturing process chain. Most surface treatment processes are associated with a high energy intensity. As shown in Fig. 1, the energy demand of manufacturing processes tends to increase with decreasing process rates which are typical for most surface treatment processes (Gutowski et al., 2006). Especially physical vapor deposition and chemical vapor deposition processes are very energy intensive processes (Gutowski et al., 2006).

Furthermore, surface treatment processes often require chemicals with potential impact on human- and eco-toxicity. A current example for a hazardous chemical is hexavalent chromium (CrVI) in the surface treatment process chromium electroplating (Saha et al., 2011). Another example are surface finishing processes such as grinding requiring cutting fluids to cool and lubricate the contact zone (Denkena and Tönshoff, 2011). Today, most cutting fluids are a mixture of oil or water with additives that can cause diseases of the skin and respiratory tract (Brinksmeier et al., 2015).

Life Cycle Engineering (LCE) takes the environmental dimension as basis and boundary for economic and social sustainability. Systematic LCE aims to prevent problem shifting between life cycle stages. Although, in the last decades LCE has been applied to many other industries and engineering disciplines (e.g. lightweight and carbon fiber applications (Dér et al., 2018, Herrmann et al., 2018)), for the specific requirements of surface engineering no holistic approach can be found.

1.1. Surface engineering

In surface engineering (SE), a surface/substrate composite system is created to achieve properties which cannot be achieved

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without this composition (Huang et al., 2012). It describes the process to enhance the properties of a component by modifying or coating its surface (Hutchings and Shipway, 2017). Surfaces must be able to fulfill different requirements in the use phase of a component depending on the application (Tillmann and Vogli, 2006) (see Fig. 2):

To fulfill these requirements various manufacturing processes are available. To select the right surface treatment processes, manufacturing processes that are applied influence the surface’s properties of a product are identified. The German standard DIN 8580 classifies manufacturing processes in six main groups (Dér et al., 2018). The most common surface treatment processes can be found in the three main groups coating, cutting and changing material properties (see Fig. 3).

The main group coating contains all surface treatment processes, which are the result of an additional coating on a substrate. Coatings can be applied from liquid, solid, gaseous, vapor or ionic state of the coating material. Examples are:

- Liquid state: hot dipping, dip coating, painting
- Solid state: thermal spraying, electrostatic coating
- Gaseous/vapor state: physical vapor deposition, chemical vapor deposition
- Ionized state: electro- and chemical plating

In the main group cutting manufacturing processes which can be used to directly influence the surface topography of a product by changing the surface itself. Especially finish machining in cutting with geometrically defined and undefined cutting edge can be accounted as surface treatment process. The focus is set on modifying the product surface’s properties and not to shape the geometry of the product. All types of cleaning processes are also accounted as surface treatment processes as shaping the material has no relevance for these processes and they are typically the basis for further surface treatment processes.

In the main group changing material properties, processes that influence the surface layer of products can be found. Peening processes typically focus on modifying the surface hardness. Surface heat treatment processes as induction hardening and plasma diffusion processes can be accounted as typical surface treatment processes.

1.2. Life cycle engineering

Life cycle engineering aims to guide engineering activities in development, manufacturing, use and end-of-life treatment of products while considering the global sustainability goals (Hauschild et al., 2017). An essential part for the environmental assessment is the life cycle assessment methodology from DIN EN ISO 14040 (DIN Deutsches Institut für Normung e.V., 2006). To evaluate the life cycle costs, an approach can be found in the DIN EN 60300-3-3 (DIN Deutsches Institut für Normung e.V., 2005). From a life cycle perspective, the stages raw materials extraction, production, use and disposal/recycling can be distinguished. For the environmental assessment various impact categories, such as climate change or acidification are available to describe the effects on different aspects in the environment (Baumann and Tillman, 2004). Economic assessments typically only use a single currency as indicator. While comparing products or processes, break even calculations are commonly used in life cycle engineering.

2. An integrated framework for and life cycle engineering in surface engineering

To integrate the life cycle engineering principles into surface engineering, the effects of surface engineering on life cycle engineering is discussed. Based on this a conceptual framework to evaluate the environmental impact of surface treatments over the whole life cycle parallel to the surface engineering process is introduced. The framework involves all life cycle stages of the surface to avoid problem shifting. Finally, an approach for the integration of computational models from surface engineering and life cycle engineering is introduced.

2.1. Effects of surface engineering on life cycle engineering

The increased environmental impact and costs due to the surface treatment process in the production stage can be compensated by a decreased impact in other life cycle stages. Ideally, a
break-even can be reached in the early use stage or already before the usage of the product. In this section the positive and negative effects of surface treatments related to the environmental and economic impacts are discussed. In particular surface treatments have the potential for the following positive effects on the life cycle of a product, which can be categorized into three objectives (see Fig. 4):

1. Extend the lifetime of products due to:
   a. Increased wear resistance
   b. Increased corrosion resistance
2. Decrease the energy and resource consumption during the use phase due to:
   a. Reduced friction
   b. Reduced weight
   c. Reduced auxiliary use (e.g. lubricating fluids)
3. Allow the use of less resource intensive base materials

The lifetime of products can be extended by an increased wear and corrosion resistance. A break-even typically can be reached when the product without surface treatment needs to be replaced. Reducing the number of replacements also reduces the maintenance efforts and decreases the risk of prematurely failures (Mobley, 2002).

The life time extension only brings a positive impact in case the product typically needs to be replaced during the lifetime of a product, e.g. machining inserts.

The increased surface quality has the chance to decrease the environmental and costs during the use phase. A reduced surface roughness, e.g. in ball or linear bearings, decreases the friction and therefore the energy demand for these systems. The following surface properties have the chance to influence the use phase significantly:

i) Corrosion resistance
ii) Wear resistance
iii) Tribological behavior (i.e. roughness)
iv) Optical behavior (i.e. reflection and anti-reflection properties)

Surfaces with a significant increased wear and corrosion resistance can make auxiliaries as lubricating or cutting fluids obsolete. Hard and smooth (low roughness) tools reduce the heat development in cutting processes and make cutting fluids for specific materials and machining operations obsolete (Weinert, 1999). Removing the cutting fluid from the machining process also allows to remove the whole cutting fluid periphery which accounts for up to 50% of energy consumption of an automotive components manufacturing line (Bode, 2007).

Reflection and anti-reflection effects from coatings can be used for windows in buildings. Anti-reflective windows have the potential for a positive impact in areas with a high heating demand (Rosencrantz et al., 2005) and highly reflective windows in areas with a high cooling demand (Chow et al., 2010). The reduced heating/cooling demand allows to decrease the dimensions of the HVAC system. Especially in case of vehicles and other mobile applications this decreases the weight to be moved and therefore the energy demand.

Beside the compensation of the environmental impact in the use-phase, surface treatment processes also can decrease the environmental impact during the raw material production phase in case less resource intensive materials can be used as substrate. For example, in sanitary applications chrome plated plastic parts can replace stainless steel parts or coated screws can replace stainless steel screws for many applications.

Beside the mentioned positive impacts of coatings, the following negative impacts or additional efforts need to be considered in a life cycle engineering approach:

1. Increased complexity of manufacturing process
2. Separation process at the end-of-life required

Surface treatment processes are typically energy intensive processes (see Fig. 1) and can be associated with the use of hazardous chemicals. Also the manufacturing process chain becomes more complex and many surface treatment processes have different process times and characteristics compared to the prior shaping process. Also the requirement for energy and resource flows from the technical building system can differ significant.

A relevant issue especially for coated products is the end-of-life, where surface treated products can have a higher environmental impact due to the higher effort in the material separation process. In most cases the recycling of coated products is difficult and the cost for recycling higher than for landfilling (Bach et al., 2000).

2.2. Framework

Fig. 5 shows the life cycle of coated products, using the example of cutting inserts. The life cycle becomes more complex compared to cutting insert without coatings, but technological, environmental and economic benefits can be achieved in single life cycle stages.
In the raw materials extraction stage the additional coating material must be extracted or retrieved from a recycling process. Typical coating materials as Zinc, Nickel or Titanium have a significant higher amount of embodied energy and carbon footprint compared to typical substrate material (Ashby, 2013), but most coating technologies deposit only thin films in the range of μm. In case a cutting or changing materials properties process is applied, only auxiliary materials are required.

In the production stage the product first needs to be shaped and then to be surface treated. Coating materials also have to be prepared for the use in surface treatment processes. As already stated before and in Fig. 1, the specific energy demand per kg material deposited or removed is high and often hazardous chemicals are required.

In the use stage a surface finished product should be able to fulfill technological, environmental and economic benefit. Compared to modelling the manufacturing process, modelling the use stage requires an interdisciplinary approach, depending on the specific product. Often the functional unit for the life cycle assessment must be adjusted and specific procedures to allocate the environmental and economic load on the functional unit be introduced. In case of coated windows, it becomes necessary to model the energy saving of the HVAC system of a building or vehicle. If a cutting inserts allows to change process parameters, the change in energy demand of the machine tool has to be considered. This examples shows, that it can become necessary to extend the scope to model all relevant effects.

At the end-of-life products need to be disposed or ideally recycled. In case the product is landfilled, the impact often remains similar for coated products, therefore possible recycling routes should be taken into consideration. In conventional steel recycling processes coatings evaporate and are collected in the gas cleaning, oxidize, report to the slab or also can be dissolved in the steel (Björkman and Samuelsson, 2014). For example zinc coatings evaporates during the steel melting process and do not influence the steel quality. Chromium remains in the steel and the chromium share in electric arc furnace steel gradually increases. Oda and colleagues reported that the chromium share will reach 0.24% in 2030 (Oda et al., 2010).

2.3. Model integration

For an integrated life cycle assessment during the design phase of a product, computational models for all life cycle phases are required. Models from surface engineering can be used as basis to predict the environmental impact during the manufacturing and the usage phase. In surface engineering, the integrated computational materials engineering approach allows coupling of process, component and materials models in a multiscale simulation environment (Allison et al., 2006). It allows to reduce the effort to develop new products and manufacturing processes as well as to increase the performance of both.

For LCE also models for the raw materials and the end-of-life processes must be available (see Fig. 6). As already described, these models can come from different disciplines and need product’s properties as input parameters such as wear and corrosion resistance.

An integrated approach shall allow to combine models from surface engineering and LCE. Cerdas and colleagues described an approach to integrate life cycle assessment calculations within other engineering models (Cerdas et al., 2018). In Fig. 6 this approach has been transferred to the case of surface engineering. The models from the integrated computational materials engineering can be used as part of the life cycle modelling and contribute towards more precise life cycle models. Further an integrated model environment allows modelling interdependencies between the surface quality and the behavior in the use phase to obtain a trade-off between these for specific use cases.
2.4. Evaluation

The integrated computational approach allows a comprehensive evaluation of the environmental and economic effects over the whole life cycle. Depending on the objective, conflicts between different objectives can be balanced a priori. Further, different life cycle and surface treatment scenarios can be calculated and evaluated regarding their life cycle potential. The developed approach allows estimating the environmental and economic load under which a surface treatment can cause due to savings in later life cycle phases. By this energy and resource intensive surface treatment methods can be excluded for some applications.

3. Application: metal cutting tools

Coatings are widely used for metal cutting tools to enhance their wear resistance and performance. About 80% of cemented carbide cutting inserts are coated with a wear resistance hard material coating. State of the art are chemical vapor deposition (CVD) and physical vapor deposition (PVD) to deposit hard materials with primary metallic bonds, such as TiN or TiC, and covalent bonds as diamond. (Klocke, 2011)

After sintering, cemented carbide cutting inserts are ground to their final shape. This process is energy and resource intensive due to the high hardness of cemented carbides. Klocke and colleagues as well as Kapuschewski and colleagues reported that the energy demand for grinding can reach up to 75% of the primary energy demand of cutting inserts, while the share for the PVD process can be nearly neglected with 1–2% (Klocke et al., 2013, Kapuschewski et al., 2011).

Klocke and colleagues compared uncoated and (Ti,Al)N PVD coated cemented carbide cutting inserts for a milling process. Assuming that the end-of-life of a cutting insert is reached at a flank wear of 200 μm the coated tool life was extended by 57% from 4,200 to 6,600 mm cutting length. Besides this, it was possible to reduce the energy demand of the machine tool as the process time by 67% due to a higher cutting speed and less tool change durations (Klocke et al., 2013).

Based on this data and the assumption that the PVD coating process results in an additional impact of 2% for the production process (Klocke et al., 2013, Kapuschewski et al., 2011), the Fig. 7 has been drawn. Environmental benefits can be obtained from the extended life-time and the decreased energy demand during the use phase in the machine tool. However, the recycling process has been neglected due to the lack of separate data for coated and uncoated (Ti,Al)N PVD coatings.

For recycling, coatings can be separated from the cemented carbides by a fragmentation and oxidation process (Kuang et al., 2019) or leaching (Gürmen et al., 2020). The cutting insert manufacturer Sandvik Coromant industrialized a recycling process for coated cutting inserts and reports about 75% less energy and about 40% less carbon dioxide emissions compared to the use of virgin materials (Hallberg, 2010).

However, it has to be noted that the cutting insert coating must fit to the requirements (materials, parameters and lubrication) from the cutting process in order to archive environmental and economic benefits. In the study by Klocke and colleagues also CVD coated cutting inserts were tested which coating could not resist the thermomechanical load and therefore could not archive technological, environmental or economic benefits (Klocke et al., 2013).

4. Conclusion, discussion and outlook

This study showed that the application of life cycle engineering in surface engineering has the chance to rate the environmental and economic effects of surface treatment technologies. A framework was introduced and applied to coated and uncoated cutting inserts, which showed clear environmental benefits for the coated tools.

It has to be mentioned critically that there is a lack of available data for possible recycling routes of coated products. Simply considering landfilling for coated products neglects the difficulties in the recycling process and should be avoided as landfilling typically results in the same negative impact for coated and uncoated products.

A recent trend in science is the functionalization of surfaces for example with sensorized thin films (Biehl et al., 2008). This functionalization goes beyond conventional surface engineering and asks new concepts to assess the environmental impact of these surface treatments methods.

CRediT authorship contribution statement

Alexander Leiden: Conceptualization, Data curation, Methodology, Visualization, Writing - original draft. Peter-Jochen Brand: Data curation, Writing - review & editing. Felipe Cerdas: Formal analysis, Writing - review & editing. Sebastian Thiede: Conceptualization, Methodology, Writing - review & editing. Christoph Herrmann: Supervision, Conceptualization, Writing - review & editing.

Reference
