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Life cycle assessment of cubic boron nitride grinding wheels

Marius Winter [a, c, *], Suphunnika Ibbotson [a, b], Sami Kara [a, b], Christoph Herrmann [a, c]

[a] Joint German-Australian Research Group on Sustainable Manufacturing and Life Cycle Management, Germany
[b] Sustainable Manufacturing and Life Cycle Engineering Research Group, School of Mechanical and Manufacturing Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
[c] Sustainable Manufacturing and Life Cycle Engineering Research Group, Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany

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A B S T R A C T

To reduce the environmental impacts caused by manufacturing processes science, and industry want to identify hotspots and to derive improvement measures. One of those contributing manufacturing processes is grinding using synthetically produced cubic boron nitride (cBN). CBN grains are broadly applied for super abrasive materials in the production of high-precision grinding wheels. The shape, size and volume concentration of the cBN grains have a major impact on the technological results (workpiece roughness, tool wear, temperature, etc.) of the grinding process and on the economic value of the grinding wheel. Despite the technological results and the economic value, the contribution of cBN grinding wheels to the overall environmental impact has not been fully investigated and understood. A key method to calculate the environmental impact is life cycle assessment. However, an essential requirement is the availability of the used material and energy data during the life cycle stages of grinding wheel material, production, application and disposal. This paper gives an overview regarding the needed materials and energy during the different life phases of a cBN grinding wheel. On this basis, the detailed environmental impact of the grinding process is presented in a case study.

1. Introduction

Grinding is a finishing process with a geometrically undefined cutting edge. This process is used to achieve certain technological workpiece characteristics such as a fine surface finish, high geometrical accuracy and specific material properties. In industrial countries, this process accounts for 20–25% of their total expenditures of all machining processes (Malkin and Guo, 2008). Approximately 28% of the machine tool stock (about 740.000) installed in the European Union (EU27) are grinding machines (state 2009) (Schischke et al., 2012). The process can be used for the machining of hard-to-machine materials such as cemented carbide, carbon and alloy steels and austenitic nickel–chromium-based super alloys. For this purpose, different workpiece shapes can be ground utilising surface and rotational process kinematics.

The grinding process can be described based on the interactions between the input process variables and the achieved output objectives. These complex interactions are divided into three main compositions and are depicted in Fig. 1. The interactions include the relations of the process input variables (left side), the grinding process (centre) and the influences on the output objectives (right side). The left side of the figure presents the three groups of process input variables including the workpiece properties, the process parameters and different enabling factors. The centre of the figure illustrates the interactions of the groups, which are decomposed into three layers. The top layer presents the main purpose of the grinding process with the product attributes transformation. This layer is influenced by the required workpiece properties. The achievement of these properties is a function of the selected process parameters, such as cutting depth (a_e), cutting speed (v_c), workpiece speed (v_w) and dressing feed (v_{fad}). The enabling factors have, in connection with the process parameters, influence on the resource and energy conversion during the grinding process. Subsequently, the layers of a grinding process influence the three output objectives on the right side. They are distinctively classified as technological (surface roughness, geometrical accuracy, etc.), economic (cost and time)

* Corresponding author. Sustainable Manufacturing and Life Cycle Engineering Research Group, Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany.
E-mail address: m.winter@iwf.tu-bs.de (M. Winter).

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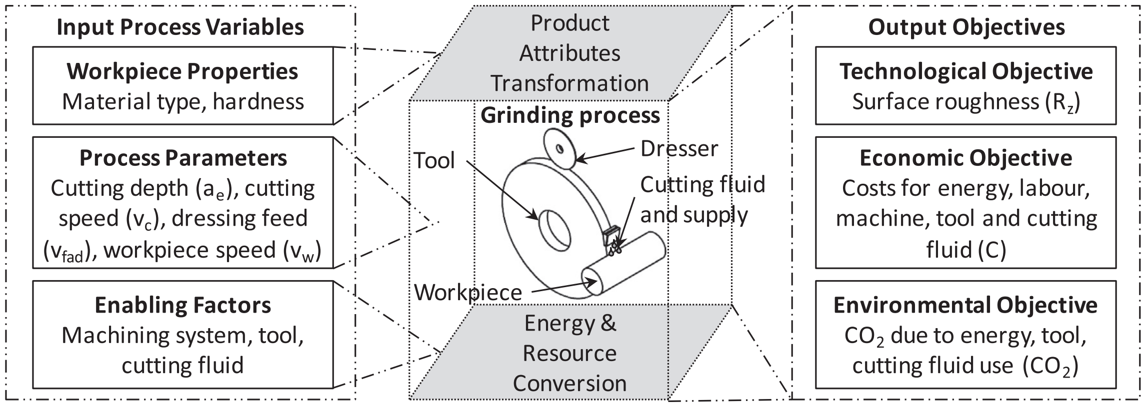

Fig. 1. Composition of a grinding process (adapted from (Winter et al., 2013) and (Li et al., 2012)).

and environmental (carbon footprint, resource depletion, etc.) objectives.

The technological and economic objectives are the main goals of the grinding process. However, the environmental objective is of increasing importance due to changed legislation, regulations and customer requirements (Duflou et al., 2012). It is a challenge to achieve all objectives due to their antagonistic effects. To achieve a good surface roughness, for example, the cutting depth should be low. However, a low cutting depth increases the process time and inclines the cost and environmental impact due to a higher energy demand.

A number of studies have been conducted to investigate the environmental impacts of a grinding process. However, they often considered the assessment for the carbon dioxide equivalent (CO_2eq.) of the raw materials and production of a grinding wheel in a simplified manner (Winter et al., 2013). They also excluded the overall environmental impact, or only considered the environmental impact due to a combination of energy, cutting fluid or grinding wheel demand, while not changing the process parameters. An environmental impact assessment of the grinding wheel in details has not been possible due to the limitation of data availability as a result of the confidentiality issue (Li et al., 2012).

To reduce the environmental impact, an understanding of the system is required to avoid problem shifting and to handle goal conflicts. It is possible to demonstrate the importance of system understanding and how to derive recommendations for industry and future research by using the grinding process as an example. Therefore, this research collected extensive data for the grinding wheel production as well as experimental data to examine the needed resources and energy flows during the operation of the grinding process. A life cycle assessment (LCA) is used to calculate the environmental impact of a grinding wheel in different life cycle phases including:

- Impact assessment of one grinding wheel (cradle-to-gate)
- Impact assessment of the grinding process for producing 12,000 workpieces (cradle-to-grave).

This paper provides a theoretical background of a cBN grinding wheel and LCA in Section 2, which also highlights previous research related to the LCA of cBN grinding wheels and research gaps. Subsequently, Section 3 presents materials and methods. The background information and data of materials and production processes that are used to produce a cBN grinding wheel as well as material flows of the main ingredient, namely cBN abrasive grains, bond systems, pore builder and other additives are described in Section 3.1. A methodology of LCA and case studies of both cradle-to-gate and cradle-to-grave are also given in Section 3.2. The information is based on input data obtained from extensive literature as well as experimental data, which is then used to generate results in Section 4. LCA results are discussed for both, a grinding wheel and its life cycle, considering varying grinding process parameters during the usage life cycle stage. Section 4 demonstrates results found in the hotspot analysis and the sensitivity analysis. The conclusion of this investigation is presented in Section 5.

2. Theoretical background

2.1. Application, structure and materials of grinding wheels

The composition and structure of the grinding wheel are the major influencing factors in achieving the prescribed technological characteristics. Four main grinding wheel components can be distinguished: the abrasive grains, the bond, the pores and (depending on the grinding wheel design) the wheel hub (Webster and Tricard, 2004). The abrasive grains are embedded and linked by the bond. Due to the irregular shape of the abrasive grains, pores are naturally created or can be induced by artificial pore builder. Pores are needed for cutting fluid transport into and chip clearance out of the process zone (Davis, 1995). The abrasive grains and the bond are mixed and pressed to a green body to form either a full body abrasive wheel or an abrasive layer or segments. Subsequently, the body, the layer or the segments are cured and then coated on a wheel hub (see Fig. 2).

The grinding wheel performance and characteristics are significantly influenced by the volume ratio of abrasive, bond and pore to the total wheel volume. For example, the increase of bond content, if the abrasive content is kept constant, leads to a reduction of the pores and to an increase of the grinding wheel hardness. The reason is the creation of stronger bond links between the abrasive grains (Davis, 1995). The increase of the pore volume leads either to a reduction of cutting edges or bond strength. Apart from this technological impact, the volume ratio of abrasive and bond to pore has also an environmental and economic impact due to the amount of used materials.

The abrasive grain materials are distinguished into two groups: the conventional abrasives and the super abrasives. The conventional abrasives commonly enfold grains made from fused or non-fused aluminium oxide, zirconia alumina and black or green silicon carbide. The super abrasive grains are made either from diamond or cubic boron nitride (cBN) (Davis, 1995). Diamond is the hardest material followed by cBN, silicon carbide, aluminium oxide and zirconia alumina. Regarding the bond material, different types can