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Superabrasive Applications in Grinding of Crankshafts: a Review

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Abstract

The crankshaft grinding process has evolved remarkably over the years, from plunge grinding processes run on several machines to completing a crankshaft on a single grinding machine featuring multi-spindles, where rough and finish grinding increments can be determined based on predicted grinding temperatures to avoid thermal damage and reduce wheel wear while simultaneously shortening the grinding cycle time.

This paper reviews the important developments of the crankshaft grinding process, primarily by analysing patented grinding methods. The technology advancement, however, is not only process related, since it extends to grinding wheel innovation which necessitates the modification of cubic boron nitride (CBN) abrasive grits and optimisation of dressing.

Introduction

Internal combustion engines using crankshafts are still the dominating type of automotive powertrain on the market. The innovation related to crankshaft manufacturing suggests that there is still an industrial demand to improve and optimise the exisiting grinding processes [1-5]. There are at least two reasons for this. On the one hand the OEMs are demanding a reduction in the cost per part, typically achievable via reducing the grinding cycle times and by employing high-performing superabrasive grinding wheels that wear less and that are not dressed excessively or too frequently. Then, improved engine designs necessitate an improvement in the performance (quality) of crankshafts through improved surface integrity (including surface finish) and by adding special demands, such as the sector roundness. The future advancements in crankshaft grinding include the implementation of innovative grinding methods, optimisation of the machine-specific dressing processes, modifications of superabrasive grains and the development of new grinding wheels tailored to technology specifics. The scenarios below review the improvements of the grinding process and then suggests a new grinding wheel design for this application.

Crankshaft grinding methods developed by machine manufacturers

The majority of grinding process innovations are included in a number of patented methodologies, primarily filed by the machine-tool manufacturers. These include Jtek Corporation, Cinetic Landis Grinding Limited, Erwin Junker Maschinenfabrik – which are the companies designing their own grinding processes and, in some cases, specifying the grinding parameters.

Toyoda Koki Kabushiki Kaisha / Jtek Corporation

The first patent focusing on crankshaft grinding goes back to 1986, where Toyoda Koki Kabushiki Kaisha (now Jtek Corporation) attempted to improve, the then state-of-the-art plunge grinding process [1]. They proposed angle plunge grinding of shoulders and adjacent cylindrical portions of a crankshaft using a grinding wheel that is thinner than the space between the shoulders. The remaining cylindrical portion is ground by axial feed in this method. Figure 1 shows the procedure of grinding a crankpin proposed by Jtek Corporation, by realising steps from A to J.

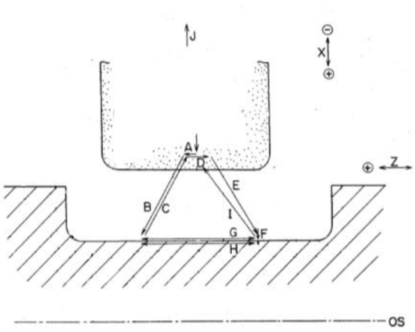

Figure 1: An angle plunge grinding method [1].

In 2006, Toyoda Koki Kabushiki Kaisha reported [2] some of the challenges associated with the above angle plunge grinding approach developed in 1986. The fact that the sidewall, the radius and the diameter are ground simultaneously led to difficulties in effectively evacuating the grinding chips as well as providing sufficient coolant into the grinding zone. This situation could lead to an increased heat generation due to wheel clogging (i.e. more rubbing) – resulting in thermal damage of the workpiece. They thus proposed to reduce the contact between the workpiece and the grinding wheel using a smaller angle when plunging into the crankshaft sidewall. This method is shown in Figure 2, where the grinding steps are implemented in the XZ, Z and X directions. Notice that the XZ path has a relatively small angular approach towards the sidewall.

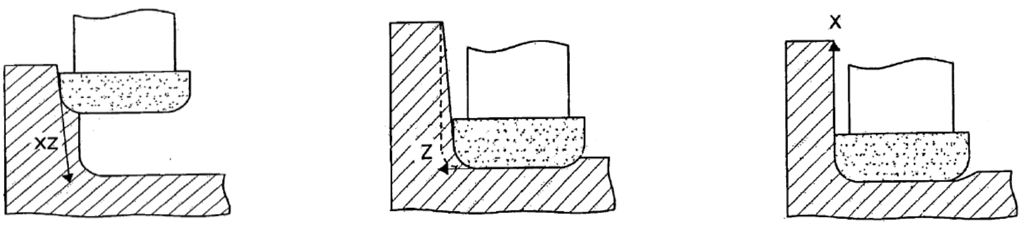

Figure 2: The grinding method steps as described in patent US 7,118,453 [2].

A new patent application published in 2008 [3] showed a further incremental improvement of the above method [2]. The motivation for this invention was a problem inherent in the process. A radius of the grinding wheel removes relatively large amount of material resulting in an accelerated wheel wear which shortens the dressing interval and can affect the geometry of ground surface.

The proposed method makes the initial pass on the sidewall using side and chamfer of the wheel rather than the radius. Figure 3 displays the prior art [2] on the left and improved method [3] on the right. The hatched part illustrates the material removed by the radius of the grinding wheel. The numbers 1-6 and A1-A6 represent the consecutive grinding steps. They suggested that this improvement results in a reduced wheel wear and thus prolonged wheel life.

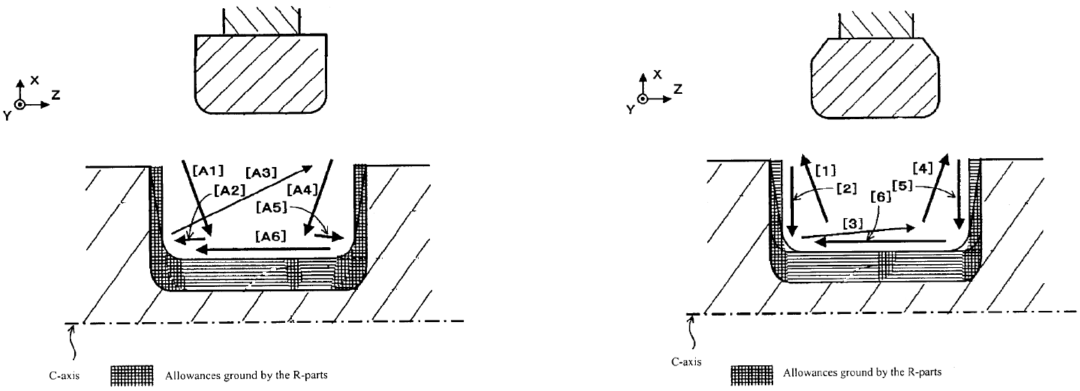

Figure 3: Prior art [2] on the left and the modified method for grinding of crankpin on the right [3].

In 2009, Jtek Corporation published another method of grinding the crankshafts [4]. In this method, the wheel is shuttling between the sidewalls (highlighted by arrows in Figure 4) thus enabling improved cooling of the sidewalls when the wheel is not in contact with the workpiece. This procedure reduces the possibility of grinding burn and reduces the wheel wear. As the wheel interacts with the workpiece at different segments, the load across the wheel profile is more evenly distributed – leading again to less wheel wear.

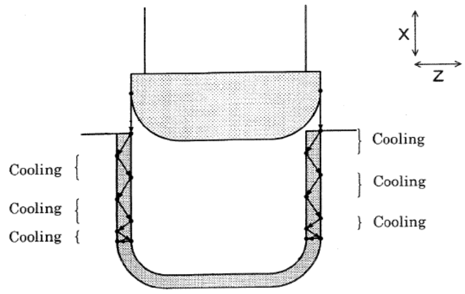

Figure 4: Shuttling of the wheel between the two sidewalls [4].

Cinetic Landis Grinding Limited

A patent from a UK based grinding machine manufacturer, Cinetic Landis Grinding Limited, was published in 2005 describing an angle plunge grinding method to grind the sidewall and the adjacent cylindrical portion [5]. The patent appears to be an advancement of the method in [1], as it finishes grinding the sidewall ahead of the cylindrical part (see Figure 5). When the cylindrical part is being finished the wheel is retracted from the sidewall, so that, no rubbing occurs. Rubbing has typically detrimental effects as it increases the risk of grinding burn, i.e. thermal damage to the workpiece. This technology has a better control of feed rates, dwells, workpiece speeds and coolant pressure/flow in each step.

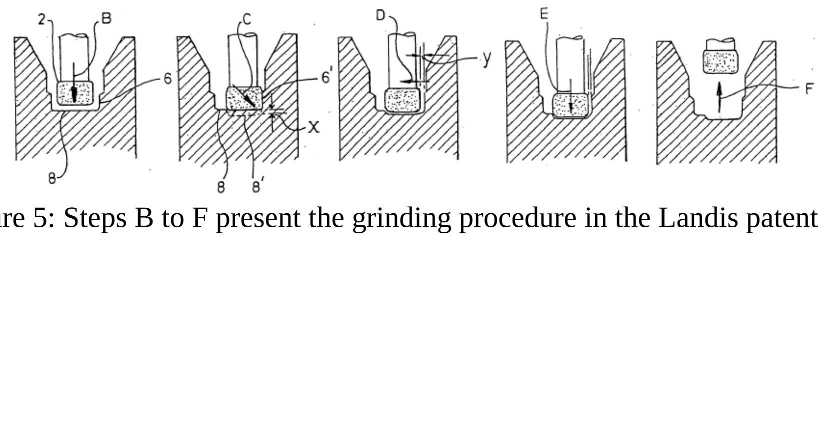

Figure 5: Steps B to F present the grinding procedure in the Landis patent [5].

Crankshaft grinding research in academia and industry

In 2003, a force model for plunge grinding method of crankshaft was developed with the objective of optimising the grinding process [6]. It has been validated experimentally on a Landis grinding machine by measuring grinding forces using strain gauges on the tail stock, head stock and work support. Good correlation between modelled and measured grinding forces has been found. In 2005 Oliveira et al. [7] compared three grinding strategies: (1) axial plunge grinding, (2) axial face grinding and (3) multi-face grinding, using primarily an experimental approach. They were able to determine the most affected areas on the grinding wheel during the process and to select the most suitable grinding conditions to reduce the wheel wear. They also demonstrated that multi-face grinding provides the best results, where material removal rate can be balanced for each step in order to achieve better process control.

A review of recent advancements of crankshaft grinding in the automotive industry is given by Krajnik et al. [8], who modelled the fundamental grinding parameters for each part of the wheel profile in the most commonly employed methods used in industrial crankpin grinding (radial plunge grinding and angle plunge grinding [6]). The background here was the temperature-based method for determination of feed increments which has also been patented and implemented by Scania CV AB [9]. In this innovative approach to crankshaft-grinding, axial and radial increments are simultaneously feeding the grinding wheel into the workpiece in a temperature-controlled manner. The increments are calculated in a way that the maximum surface temperature of the workpiece does not exceed the temperature threshold causing thermal damage [9] according to the formula:

$$\Theta_m=1.064/(k\cdot\rho\cdot c_p)^{1/2}\cdot e_w\cdot aggr(s)\cdot Q_w'(s)/(l_c(s)\cdot v_w) \quad \text{(Eq.1)}$$

where Θ_m is maximum surface temperature, k, ρ and c_p are workpiece-material related constants, l_c is the geometrical contact length between the workpiece and the wheel, v_w is the workpiece speed, $Q_w'(s)$ is the specific material removal rate determined for an arbitrary point on the grinding wheel profile, e_w is specific grinding energy into the workpiece, which depends on aggressiveness and can be experimentally determined as proposed in the Scania patent application [9]. Aggressiveness *(aggr(s))* is a non-dimensional parameter proportional to maximum chip thickness squared [10] and is calculated for each part of the grinding wheel profile.

To assess the performance of the temperature-based model [9], it has been compared to the radial and angle plunge grinding processes, commonly used by the automotive OEMs [8]. Figure 6 shows the predicted maximum surface temperatures for the three methods. The temperature-controlled method demonstrates that only full understanding of the grinding process allows to have a control over grinding temperatures. Here the productivity can be pushed to the limit (temperature-controlled case of 550 °C) or to improve the surface integrity by reducing the temperature to 450 °C in the final six increments of the grinding cycle. Another revealing point here is that some established technologies provided by machine manufacturers are far from optimum, such as, the radial-plunge method leading to highest grinding temperatures in the finishing increments. This example clearly demonstrates the need for process innovation also by the grinding end-users – in this case the automotive OEM.

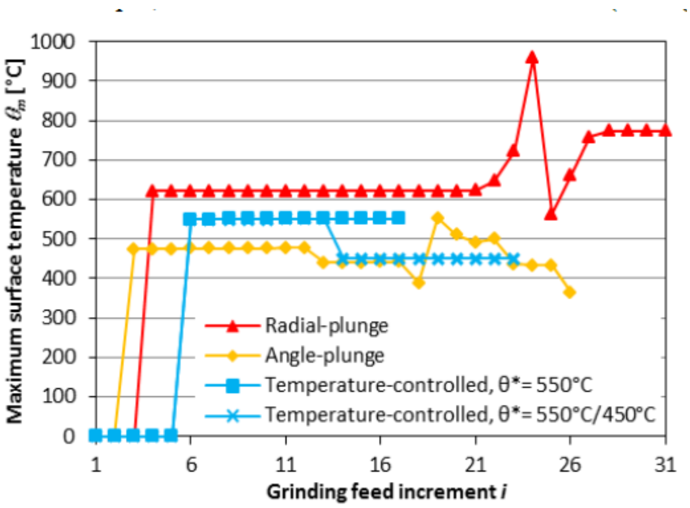

Figure 6: Comparison of standard grinding processes with temperature-controlled process [8].

Grinding wheels for crankshaft grinding

The grinding method (process) together with grinding wheel performance determine the success of the technology. One motivation for the development of new grinding methods in crankshaft production has been excessive and uneven grinding wheel wear, leading to high tool costs for the end-users. Uneven wheel wear is especially pronounced in the radial plunge grinding process, where the wheel radius takes the majority of the load during grinding of sidewalls. This results in the formation of a step on the grinding wheel radius and necessitates more-frequent-than-necessary dressing intervals – again increasing the overall tool costs.

In general, research on grinding wheels has been conducted independently of the developments of grinding methods. Now, in view of the specifics of crankshaft grinding, it is essential to understand the fundamentals of the grinding wear mechanisms in order to improve the performance through longer tool life and more uniform wheel wear. Grinding processes mainly promote two wear mechanisms: attritious or abrasion wear and fracture wear [11]. Abrasion wear uniformly enlarges a wear surface (wear flats), whereas fracture wear tends to change the general shape of the grit. Fracture wear is generally caused by a combination of thermal and mechanical stresses induced into the grit [11]. Depending on the grit type, application, process conditions and workpiece material, the wear mode can be dominated by abrasion, fracture or both mechanisms.

In crankshaft grinding applications, non-uniform wheel wear dictates the dressing of the grinding wheel. Radhakrishnan et al. [12] conducted one of the earlier studies of grinding wheel wear on the radius. They determined that wheel wear on the radius can only be corrected by dressing, which reduces the grinding tool life. They proposed setting up a force threshold to help determine the dressing interval. In a subsequent paper [13], they have focused on minimising the wear on the radius of the wheel by grooving the grinding wheel on the side wall, including a radius [13], which led to reduced grinding forces and reduced grinding wheel wear via reduced friction, improved cooling and cleaning capability.

Jackson has extensively researched bond materials used in the making of grinding wheels [11, 14]. The components of vitrified bond wheels and how these affect the wheel manufacturing process and the wheel wear were systematically reviewed [11]. Jackson concluded that grinding wheel composition is a complex system, where each of the constituents can be a variable that affects tribological properties like wheel wear and friction.

In the grit domain, it is well known that CBN grits possess superior properties in comparison to conventional abrasives. CBN has great hardness (Figure 7, left), high thermal conductivity, and is chemically inert. The CBN grit type portfolio has grown significantly over the years. This enables choosing the suitable grit type for particular application based on their properties which are normally ranked depending on the size, toughness and thermal stability (Figure 8).
Using a CBN grinding wheel in crankshaft application has become a norm [1, 3, 5, 9] since it enables higher productivity. Comley et al. [15] showed that when using electroplated tool in rough grinding of crankshaft, the material removal rates could be pushed up to 2000 mm^3/mms without encountering thermal damage to the workpiece.

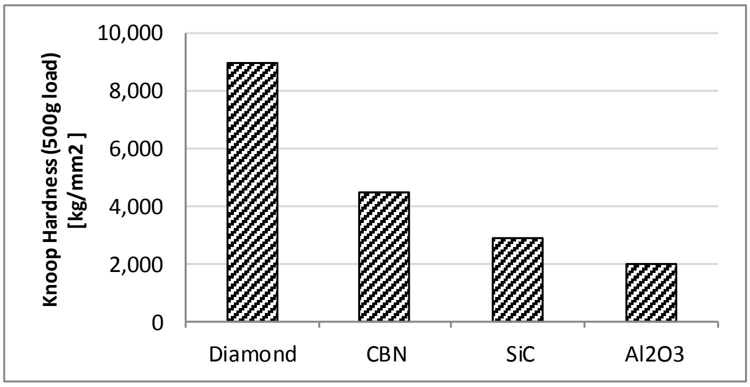

Figure 7: Hardness of superabrasives and conventional abrasives.

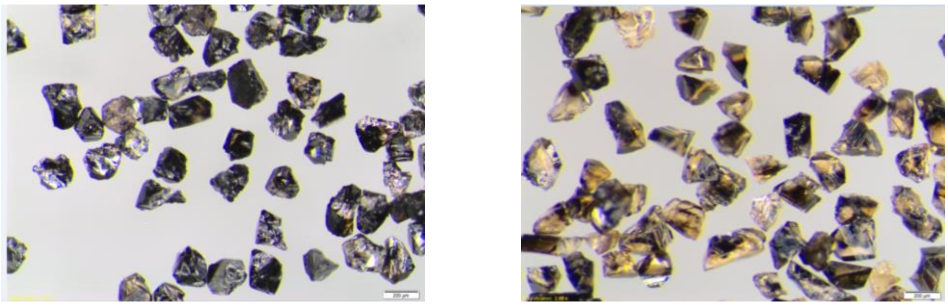

Figure 8: Two CBN grit types from Element Six having very different properties: on the left is ABN200 which is more friable and has poorer thermal stability; on the right is ABN800 which has high toughness and high thermal stability.

In recent years there has been more customising of grinding wheels to suit particular application. One example is a recent patent application published by Jtekt Corporation [16], proposing a wheel that consists of two different bond formulations and abrasive-grit-sizes (Figure 9) in order to overcome wheel-wear problems associated with their specific application of radial-plunge crankshaft grinding.

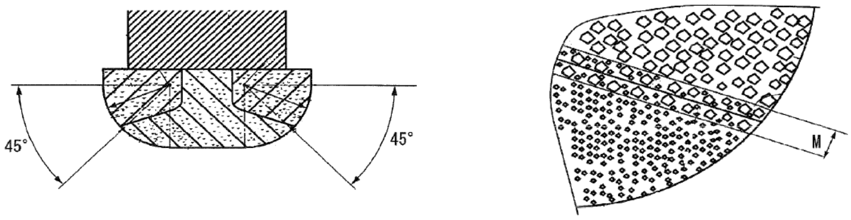

Figure 9: Cross-section of the abrasive layer structure with three distinctive sections (left); difference in abrasive size between the two layers and the mixed layer in between (right) [16].

The patent application proposes a wheel design that addresses two specific problems in their use – wheel wear on the radius near the sidewall and surface finish on the bearing surface – and proposes a grinding wheel with two portions containing different grit sizes and bond formulations. A first region, at the bearing surface and extending into the radius, contains smaller grits in a softer bond to obtain a better surface finish; and a second region, at the sidewall and extending into the radius, contains larger grits in a harder bond to minimize wheel wear.

Dressing of grinding wheels used in crankshaft grinding application

Grinding wheel wear causes wheel topography changes which result in increased grinding forces and deteriorated surface finish. This requires dressing in order to avoid potential thermal damage on the workpiece and geometrical inaccuracies. Grinding performance after dressing strongly depends on the dressing tool, dressing-system layout and dressing parameters used. The first two are normally predefined by grinding tool manufacturers and machine builders, respectively. The only variable that can be easily changed to suit the workpiece surface requirements are dressing parameters.

Depth of dress, overlap ratio and speed ratio are normally specified to achieve particular surface finish. Malkin and Murray [17] have shown that if the chosen dressing parameters generate finely dressed wheel the grain tips are flattened. On the other hand, if the dressing parameters produce a coarse wheel, the grains fracture. This is particularly typical for conventional grinding wheels. A parameter called interference angle has been presented in the same paper [17] that explains the severity of dressing. It also affects the dressing energy.

Brinksmeier and Cinar [18] showed that CBN grinding wheels topography is “closed” after dressing which means the grit protrusion is small. They have also explained the severity of dressing by implementing a collision number which combines some of the standard dressing parameters and represents the collision frequency of the CBN grits on the grinding wheel with diamonds in the dressing roll.

Dressing set up depends on the grinding application and the dressing requirement of the wheel. If only surface grinding of the workpiece is required then a traverse dressing of the grinding wheel is sufficient (see Figure 10, left). However, if the application is crankpin grinding where the grinding wheel needs dressing on the periphery, the radius and the sidewall, the dressing strategy is more complex. One of the possibilities is the cross-axial dressing which allows dressing of over 180˚ (see Figure 10, right) [19]. This dressing layout is also found in a particular crankshaft grinders, and has many benefits, such as uniform dressing geometry around the different portions of the wheel achieved with a single geometry of a dressing roll.

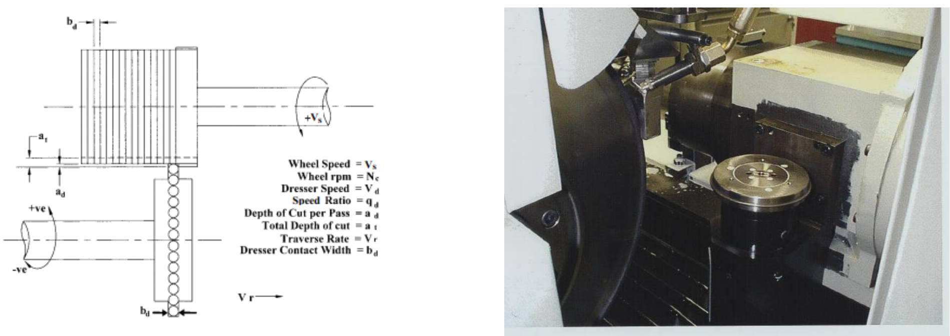

Figure 10: Basic traverse dressing (left); cross-axial dressing (right) [19].

Summary

This paper reviews the various aspects of crankshaft-grinding technology: from methods developed by machine manufacturers, recent process advancements in the automotive industry, to grinding wheel innovations and dressing solutions. A number of processes have been identified and most of them are based on angular plunge grinding. The latest patent application [9] in the field has analysed the fundamentals of the grinding process, and designed an approach to control the surface temperature around the profile of the ground workpiece. In this way, the process can be run close to grinding-burn threshold leading to higher productivity. The motivation for this development lies also in localised wheel wear and thermal damage of the workpiece when employing current grinding technologies on the market, such as the radial-plunge grinding method.

A review of grinding wheel literature has not revealed a significant amount of research focusing on crankshaft applications. The main conclusion is that CBN grinding wheels are now industry standard, with limited use of conventional grinding wheels. A more crankshaft grinding focused patent application from 2017 [16] has been found describing a grinding wheel with customised composition for different parts of crankshaft. This suggests that the wheel manufacturers are now cognisant of the complex process conditions and associated behaviour at different locations on the wheel in this particular application and looking to the abrasives at least in part for possible solutions. There is much room for improvement. However, the key is to understand the grinding fundamentals of this application; for example the crankshaft portions are subjected to more or less aggressive grinding, whereas the grit loads are highly localised.

Dressing significantly affects grinding wheel performance, and standard dressing parameters might not be sufficient to optimise dressing using fundamentally different dressing-system layouts developed by machine builders. Models have been suggested that combine some of the dressing parameters and describe the severity/aggressiveness of dressing. However, similar to grinding tools, very little research has been focused on dressing of grinding wheels for crankshaft application. As the crankshaft design sets different quality-related requirements and specifications for different portions of the workpiece, different points on the grinding wheel profile are subjected to different grinding conditions/loads there are consequently different requirements for the grinding wheel. This can be achieved by customising the grinding wheel as well as by optimising its dressing. It is thus crucial to understand the different dressing layouts mounted in the machines and to optimise dressing for different portions of the wheel.

Much progress has been made in grinding of crankshafts has been made, especially on grinding methods (process innovation). However, based on this review it is concluded that more focus on the development of customised abrasive grits and grinding wheels (product innovation) is required and that optimisation of the dressing processes by considering the specific geometries and kinematics of the dressing-system layouts on the different machines would also be beneficial.

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