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CIRP-1809; No. of Pages 4
ARTICLE IN PRESS
CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Development of a patterning system for vitrified CBN wheels based on modal analysis

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ARTICLE INFO

Keywords:
Dressing
Cubic boron nitride (CBN)
Wheel patterning

ABSTRACT

One of the alternatives under development by industry to reduce tailpipe emissions in internal combustion engines is the texturing of the crankshaft bearings using patterned grinding wheels. As modern industrial grinding solutions for forged crankshafts are based on vitrified CBN wheels, a new approach is needed for rotary dressing patterning. This paper describes the development of patterning system for vitrified CBN wheels based on modal vibration analysis. Aspects related to the device design, modelling and simulation of the texturing process are discussed in the paper. The obtained results reported in this paper indicate a high potential for industrial application.

1. Introduction

Since the last two comprehensive CIRP reviews on the advances in engineered surfaces in 1999 [1] and 2008 [2], the manufacturing of “engineered”, “structured” or “textured” surfaces have become a topic of great interest in the manufacturing community. The addition of functionality to precision surfaces is a viable alternative to improve performance of mechanical components under service, by promoting lubrication [3], reducing flow loss in aerodynamic components [4] and friction in cylinder liners of combustion engines [5]. Textured surfaces are also being manufactured to store information [6] and to improve performance of optical elements [7,8]. For advanced applications, surfaces are being designed inspired by observations of examples found in nature [9].

A variety of manufacturing technologies are used to produce textured surfaces, with processes grouped according to the physical aspects involved [2]. In the category of material removal processes, grinding arises as a competitive solution to replace time consuming and expensive additional non-conventional options, such as laser methods and chemical etching. For sliding components, hydrodynamic micro-features can be produced concomitantly with the regular grinding operation, in adapted machines, making its inclusion effortless in the process chain.

The production concept of textured parts by grinding using patterned wheels was first introduced in CIRP community in 2010 [10] and further developed in 2013 [11]. To produce hydrodynamic cavities in parts with controlled profile constrains for special bearing applications, a simulation software tool was developed. The final texture profile prediction was done according to the grinding kinematics, wheel and part dimensions and hardware limitations of the dressing unit. A good process control was achieved and the feasibility for industrial application was demonstrated [12].

The users of this technology are now requiring a technical solution for the patterning of superabrasive tools, as most of the recent industrial grinding of crank bearing surfaces are being developed using vitrified CBN wheels. Therefore, a proposed solution for patterning CBN wheels needs to include a dressing spindle and a diamond rotary disc.

The combination of much higher dressing system mass and wheel speeds brings additional challenges for the system design. System frequency response required to produce the hydrodynamic features geometry gets critical considering that wheel speed during dressing is about twice as high than the one for conventional wheels. To maximize the dressing unit response when patterning vitrified CBN wheels requires appropriate unit design based on modal analysis. This approach was suggested by E. Brinksmeier during the 2017 CIRP STC G winter meeting discussions. This suggestion has solved the response problem and the work presented here shows the main results obtained in this innovative dynamically designed dressing unit for the patterning of vitrified CBN wheels.

2. Design requirements

2.1. System characteristics

Regardless the wheel type, the core concept for a wheel patterning system is the ability to dynamically change the dressing

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https://doi.org/10.1016/j.cirp.2018.04.076
0007-8506/© 2018 Published by Elsevier Ltd on behalf of CIRP.

depth according to the instantaneous wheel angular position for producing the desired patterning features on the wheel surface. Thus, the dressing unit has to incorporate two major elements: the dressing tool and an actuator able to provide a precise radial displacement of the tool tip at high excitation frequencies.

Unlike single point tools that are quite light and can be directly attached to a piezo actuator [12], the rotating dressing units need a diamond disc, motor and bearings. The needed patterning vibration amplitudes applied to the rotating dressing unit would then be limited by the system inertia and its lack of response at higher frequencies.

An alternative to reduce the unit's moving mass is attaching the actuator directly to the dressing disc bearings. However, the dresser bearing housing is typically designed for high stiffness, so its mechanical concept should be changed. The main requirements for a new design are: the radial dressing forces must be rigidly supported and the system must respond to the required dynamic condition.

2.2. New dressing unit concept

The proposed concept has to ensure the movement of the dressing disc at the needed frequencies. Typically, the disc is mounted at the end of a spindle shaft, close to the bearing. In order to accomplish this construction characteristic and to produce the required patterning displacement, the transversal stiffness of the bearing housing support can be weakened and attached to a piezo actuator as shown in Fig. 1. The reduction in the housing stiffness has to be combined with a reduced shaft diameter section, in order to allow the bearing displacement. Therefore, in this case, the moved mass is much smaller and consists of disc, bearing and its housing and the end segment of the shaft. As a result, it is not necessary to move the whole dressing unit, but only one bearing and the dresser disc assembly, leading to a much lower mass.

Therefore, the new dressing unit as shown in Fig. 1 consists of a dressing spindle, a shaft with a reduced diameter section (b) connecting the electric motor to the dressing disc assembly and a bearing assembly held by a weakened support (a). Together, shaft and bearing housing support grant flexibility to the dressing unit, allowing the displacement control. A connecting rod (c) transmits the movement of the actuator to the bearing housing, allowing the position control at the right stiffness. All these components are mounted on a supporting base that is attached to the CNC grinding machine structure.

Since the masses are still much higher than the ones for a single point diamond dressing and the frequency response curve of the actuator and its amplifier points to a first-order system with considerable damping in frequencies above 100 Hz, the only way to enable the needed response would be to operate this system at its first natural frequency. This was experimentally found in preliminary experiments. Thus, one of the challenges to produce the desired pattering amplitude is to select the right dimensions of the mechanical elements (shaft and support section of bearing housing) in order to tune the dressing unit natural frequency to the required frequency range for the application.

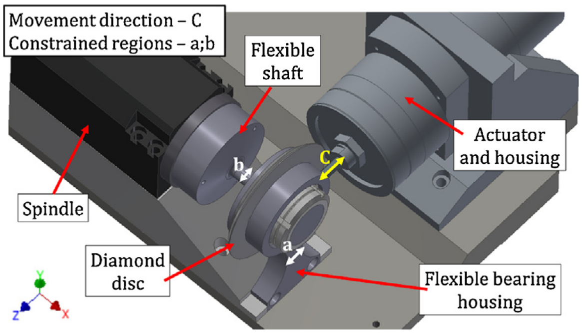

Fig. 1. Concept of the dressing unit, where a and b represent the reduced section areas and C represents the actuator moving direction.

2.3. Frequency requirements

The desired profile pattern for a bearing application can be simplified by two ramps with opposite slopes. The slopes determine the entrance and exit flows of the lubricant in order to obtain the desired increased load capacity. The relationship between these profiles is the determining factor to achieve the required tribological effect [13]. The form of interest for the application in high-performance crankshaft bearings has an ideal ratio close to 1 to 5, that is, a fluid crushing length 5 times larger than that of the intake region. In addition, the produced texture should have a depth between 6 and 12 μm and be homogeneously distributed along the crankshaft main surface. The desired shape is generic, with reasonably flexible form tolerances, and can be approached by a combination of two sine waves, as represented in Fig. 2.

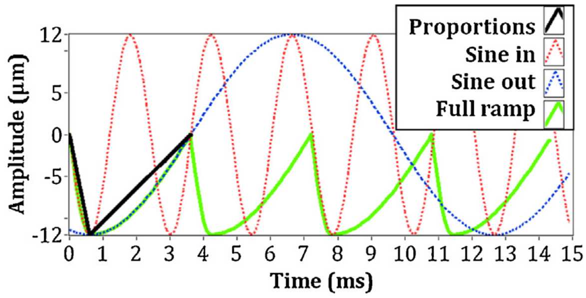

Fig. 2. Microramp profile characteristics.

The profile is formed by the segments 0 to −12 μm (*profile-in*), and −12 to 0 μm (*profile-out*). The arrangement of these profiles along the axis perimeter provides the functional improvements as detailed in Ref. [13].

As shown in the previous work [12], the geometric limitation of the grinding kinematics restricts the transcription of the micro-ramps from the grinding wheel to the part. The best result was obtained by patterning the grinding wheel with a single profile around its entire periphery, then reproducing it on the part surface n times by using the same n value as an integer rotational speed ratio between wheel and part, where n is about 20 patterns per rotation. Thus, the patterning conditions are: wheel speed (v_s) = 80 m/s or rotational frequency of 63.58 Hz and part RPM of 3.18 Hz. Since it is impossible to produce corners in these profiles, the proposed solution is to use a combination of two sinusoidal segments, shown in Fig. 2. The *profile-in* segment can be represented by a quarter sine wave at a frequency of 414 Hz. Analogously, the quarter segment of an 83 Hz sine wave curve fits the *profile-out*. The tips of the patterns show sharp edges; however, this area is not dressed on the wheel, it is a result of the grinding process kinematics.

3. System design

3.1. Numerical modal analysis

The designed dressing unit presented in Section 2.2 was numerically simulated for FEM modal analysis with two design variables: the bearing housing support width a; and the shaft diameter b (see Fig. 1). The testing parameters were: $a = [10, 15, \text{and } 20]$ mm and $b = [10, 12.5, \text{and } 15]$ mm. Two sets of constraints were applied to the base of the dressing unit: one on the fixed base and the other where the base was free to move. Force was applied in the actuator output for both sets of constraints. The assembly was then analysed using an optimally produced mesh in which the Von Mises stress varied less than 10% between two consecutive iterations, yielding a 107758 tetrahedral elements mesh. Figs. 3 and 4 exhibit the mode shape for the first natural frequency obtained in the simulation, for the fixed base condition.

In Figs. 3 and 4, it can be seen that the obtained vibration mode shape provides the necessary displacement for the

Please cite this article in press as: Silva EJ, et al. Development of a patterning system for vitrified CBN wheels based on modal analysis. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.04.076