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Dry grinding of gears for sustainable automotive transmission production

Giacomo Guerrini [a,*], Enrico Landi [b], Klaus Peiffer [c], Alessandro Fortunato [a]

[a] Dipartimento di Ingegneria Industriale, Università di Bologna, Viale Risorgimento, 2, Bologna, Italy
[b] SAMPUtensili Machinetools, Bentivoglio, Bologna, Italy
[c] Klaus Peiffer Technology LLC, Wallisellen, Switzerland

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ABSTRACT

Gear production for automotive transmissions is a rapidly growing market as manufacturers adapt to increasingly more stringent automobile fuel-efficiency requirements. Grinding is the preferred choice for finishing of automotive gears thanks to its high productivity and capability of machining heat-treated parts with very high geometric accuracy and surface quality. Grinding remains, however, the only machining process still to use lubricant, with significant costs, health implications and environmental risks. This paper presents a novel technology for grinding of gears without the requirement for oil, while still achieving necessary quality and production targets. The feasibility of this new dry process is assessed by firstly identifying threshold grinding parameters (70 m/s cutting speed; 0.4 mm/rev axial feed rate; 82% and 18% stock removed via skiving and dry grinding respectively) for avoiding grinding burn, then optimizing cutting parameters to obtain the desired gear accuracy. Gear accuracy and process productivity are found to exhibit opposing dependencies on cutting speed, stock removal and feed rate, with optimization of parameters carried out to achieve current quality and throughput standards. A comparison between results obtained with state-of-the-art wet grinding and the new process confirms the effectiveness and feasibility of dry grinding.

1. Introduction

Over recent decades, technical innovation within the automotive industry has been driven by the necessity to reduce energy consumption and environmental pollution from both vehicles and processes related to their manufacturing and transport (Orsato and Wells, 2007; Mayyas et al., 2012; Mcauley, 2003; Gupta et al., 2016). Much effort has been dedicated to development of gearboxes with up to ten speeds and dual clutch configurations, combined with smaller three or four-cylinder engines that can operate continuously under near-optimum conditions to reduce energy consumption and air pollution (Fischer et al., 2015). This change has led to an increase in demand for gear production, with growth exceeding that of vehicles themselves (IHS Automotive, 2014). A recent analysis of global transmission production predicted an increase in gear demand of 15% over the next seven years, from 95 million in 2017 to 109 million in 2024 (IHS Automotive, 2017). From a manufacturing point of view, innovation has been focused on obtaining higher productivity to meet growing demand while reducing costs and environmental impacts associated with the production chain. Manufacturing of high performance gears generally starts with soft turning of the raw material, followed by soft hobbing of the gear teeth, de-burring, heat treatment, hard-turning and finally grinding of the hardened contact surfaces (Kobialka, 2010). Grinding represents the most sophisticated production step as it is responsible for the final quality of the gear in terms of geometric accuracy and surface characteristics. The importance of grinding has increased with demand for higher efficiency and lower noise transmissions, as flank geometry and surface roughness have a profound impact on transmission performance. It remains, however, the only process in state-of-the-art gear production that continues to require lubricant, as all other gear manufacturing processes can now be performed with excellent quality under “dry” conditions (Oliveira et al., 2009). The ability to completely remove lubricant from gear production by performing grinding under dry conditions represents an important step towards a truly sustainable vehicle supply chain.

* Corresponding author. Tel: +39 0512090525.
E-mail address: giacomo.guerrini6@unibo.it (G. Guerrini).

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The use of oil in grinding creates an array of problems relating to supply, dispersion and auxiliary systems. The quantity of oil required to fill a single grinding machine is typically in the order of 2000–4000 L, of which 100–200 L is dispersed each month and must be replaced. Losses are due to nebulization during the grinding process, as well as direct fluid losses from the machine and residual oil attached to the workpiece as it is transported and washed. Loss of lubricant has a number of negative consequences for both worker health and the local environment. Furthermore, elements within swarf produced during grinding, including small metallic chips, abrasive particles, wheel bond material and oil must be separated using expensive treatments prior to disposal. Oil handling requires an extensive series of auxiliary systems that represent a non-trivial proportion of the total cost and space requirements of a grinding machine, including storage tanks, filtration systems, high-pressure pumps, oil mist separators, cooling systems, tubing for oil recovery and washing systems for workpiece cleaning. Oil handling is also responsible for approximately 75% of total energy consumption in gear grinding (Setchi et al., 2014). Dry grinding therefore has enormous potential for reducing costs and environmental impacts associated with gear finishing.

Oil lubricant employed during grinding fulfils a different role to other machining processes due to the use of abrasive grains with undefined cutting edges (Brinksmeier et al., 1999). A much lower proportion of energy remains in the chip compared to other processes, as interaction of abrasive grains with the workpiece leads to rubbing, ploughing and cutting. The first two phenomena release a lot thermal energy into the workpiece surface due to friction prior to onset of cutting (Marinescu et al., 2004). The primary technological role of lubricant is therefore not only to reduce friction at the interface between grain and workpiece, but also to remove thermal energy from the contact zone. The secondary role of oil is to remove chips from the contact zone and thermally stabilize the grinding machine. While the secondary role of oil can be accounted for with due design considerations in the grinding machine, substitution of the primary role of lubricant requires in-depth analysis of the process itself. If excessive heat is generated in the workpiece, it may be damaged or burned as thermal overloading leads to microstructural changes and degradation of surface integrity (Karpuschewski et al., 2008). Microstructural changes vary from simple oxidation to local softening and re-hardening phenomena. Such defects cause local changes in gear flank hardness and residual stresses that may eventually lead to transmission wear, vibration and noise.

Material removal during grinding is a combination of grinding speed, feed rate and depth of cut, or infeed. It can be deduced from conventional grinding theory that a reduction in infeed combined with an increase in feed rate leads to a dramatic reduction in heat development for the same material removal rate (Marinescu et al., 2004). Dry grinding can therefore be carried out in a mass-production setting by reducing infeed as much as possible and increasing the feed rate to compensate. Automotive transmission gears are presently ground in two phases; the first is a roughing pass in which approximately 80% of the material is removed, eliminating geometric errors generated by hobbing (Radzevich, 2012); the second is a finishing pass with reduced infeed to obtain the final required tooth flank roughness and geometry. A new approach has recently been developed (Landi, 2016) whereby a skive-hobbing tool, capable of removing hardened material without the use of oil, is employed prior to a single dry grinding phase. During the latter, infeed is reduced to the minimum required to remove feed marks and achieve the necessary surface roughness. The present study is intended to fully verify the integrity and geometric accuracy of gears machined using this new process.

In order to prove the feasibility of dry gear grinding, this work presents a study of generating gear grinding conducted in a real production environment. The correlation between grinding energy and workpiece thermal damage is firstly established to identify a threshold energy level under which gear surface degradation does not occur. Different degrees of burn are characterized by analyzing microstructural changes occurring at a sub-surface level on ground gear tooth flanks and helixes, as well as through hardness tests (Schwienbacher, 2008). In a second phase, optimization of process parameters is performed using a design-of-experiments (DOE) approach (Montgomery, 2001), correlating variations in each parameter with the quality of the produced component. Dry-ground gears are assessed to check their quality and prove their adequacy in terms of micro-structure, hardness, geometric accuracy and roughness.

2. Theory

2.1. Grinding burn

Grinding burn is damage induced by excessive thermal loading of a working surface during material removal. The amount of heat produced can result in microstructural modifications, leading to an abrupt change in mechanical properties that is unacceptable from a quality point of view (Marinescu et al., 2004). In automotive transmissions, gears are usually produced in carburizing or nitriding-grade steels due to the high wear resistance that these materials can provide. The gear employed in this study was a typical 27MnCr5 (1.7147) carburized case-hardened gear with chemical and mechanical properties in line with EN10084:2008, representing one of the most common choices for automotive transmissions. Grinding burn in this material is classified according to three different levels depending on the amount of heat generated in the part (Davis, 2005). The first level relates to oxidation, manifested as a dark blue color in the martensitic microstructure. This damage occurs at temperatures above 450°C, with a light straw color developing at lower temperatures and dark blue at higher temperatures. An increase in grinding temperature of this nature leads to softening, characterized by a darker microstructure near the surface where carbon has come out of solution. Though this is generally not considered severe thermal damage, reduced surface hardness can cause a decrease in wear resistance and rejection of the part. Further heating of the surface to above the austenitization temperature (730°C) leads to onset of the second grinding burn level and severe thermal damage, characterized by a white martensitic layer on the surface with an underlying dark tempered layer. Very high surface temperatures are attained within microseconds, leading to rapid transformation into martensite during cooling via thermal conduction to the cooler bulk material. This undesired quenching process creates a thin layer of brittle martensite that can easily crack. The lower temperature below the surface leads to tempering and softening in this region. Yet further increases in temperature beyond the first two levels leads to cracking due to thermal deformation; the third and final level of grinding burn (Rowe, 2014). Thermal damage is therefore caused by rapid local heating of the surface above a certain threshold energy level, with the attained workpiece surface temperature directly related to the thermal load generated during grinding.

2.2. Gear geometry control parameters

In order to check the accuracy of a produced gear, comparison must be made between the real and design geometry. The higher the accuracy, the more efficient and smooth rotation and power transmission will be, improving gear performance and lifespan. In