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The transition to a clean, dry, and energy efficient polishing process: an innovative upgrade of abrasive flow machining for simultaneous generation of micro-geometry and polishing in the tooling industry

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ABSTRACT

On account of the current different requirements in the field of finishing/polishing, e.g., reducing the finishing time, process control, ensuring a clean process, and energy efficiency, hand polishing needs to be replaced with a superior process. One alternative is abrasive flow machining (AFM). In comparison with hand polishing, AFM is an efficient process, suitable for finishing external as well as internal surfaces, which are often complex and out of reach. Due to the drawbacks of AFM, in this work a novel method of abrasive flow machining with a movable mandrel (AFMmm) is proposed and introduced through a case study from the automotive industry. As in the manufacturing sector electric power consumption is the main driver that influences CO_2 emissions, a comparative analysis of the energy efficiency of AFM vs. AFMmm is performed. The results of this work show that the application of the novel AFMmm method is capable of removing WEDM-damaged (wire electric discharge machining) surface and produces a polished surface under dry conditions, leaving the machined surface clean. Moreover, the novel upgrade of the AFM process can be significantly more energy efficient and with finishing is simultaneously able to control the micro-topography of the product. The gearing injection mold tool case study shows that the benefits are not related merely to the process, but also to the product. It offers a significant improvement in gear performance, energy efficiency in operation, as well as in fatigue life, which is extended by more than a factor of two. As a contribution, a novel clean and energy efficient AFMmm is presented, capable of synergistically shaping and polishing the geometry of the final product on a micro level and under dry conditions.

1. Introduction

The tooling industry is currently facing accelerating demands for higher quality surfaces and higher value-added products. For high-performance materials with specific property requirements (i.e., better functional properties, decreased cost, energy efficiency, and sustainability) and the ability to process them efficiently in parallel with a significant reduction in environmental burdens and safety, new product and technology development is crucial in many relevant industrial sectors, such as aeronautics, the automotive industry, rail transportation, the machine tool industry, etc.

The idea of implementing sustainability initiatives is well defined and implemented in other fields (e.g., architecture, civil engineering, etc.), but there is a dearth of such principles being implemented in manufacturing/finishing systems and technologies (Pusavec et al., 2010). Finishing processes constitute an important manufacturing activity that contributes to the growth of the EU as well as the global economy, especially in the rapidly expanding automotive and aerospace industries. The manufacturing process accounts for approximately 15% of the total manufacturing cost of finishing operations (EUROSTAT). When the surface roughness value is less than one micron, the cost of surface finishing operations again increases sharply. And the other fact is that the emerging direction in development is focused on clean and dry finishing technologies. Since 2007, the worldwide market for clean technologies has increased 11.8% a year on average, with a total value of more than €2 trillion. On the other hand, manufacturing waste accounts for approximately 40% of the EU total (hazardous waste not included), and more than 90% of the waste in manufacturing is waste from production processes.

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In the manufacturing/finishing industry, the ordinary hand polishing procedure is still used 80% of the time, and represents one of the most time-consuming, expensive, and problematic solutions in terms of health and environmental pollution. The solvents and cleaners applied to polishing solutions/media, compounds, and metal particles generate significant amounts of waste as well as small particles that enter workers' respiratory organs (Huang et al., 2013). Polishing solutions also often contain heavy metals. Later cleaners often appear in process wastewater, while solvents containing hazardous air pollutants (HAPs) and volatile organic compounds (VOCs) can be emitted into the air, released in wastewater, or disposed of in solid form.

On one hand, this data demonstrates a large market, while on the other it underlines the frightening effects on human health, if we consider workers exposed to hand polishing processes and using polishing solvents and cleaners.

In the last few decades, ultrafine-grained and high surface integrity materials have attracted considerable interest, since these high performance surface materials have higher mechanical and fatigue properties in comparison to conventional hand polished or ground counterparts (Trdan et al., 2012). The ordinary hand polishing procedure is actually one of the most time-consuming, energy inefficient, and expensive solutions. Although these drawbacks trigger both cost and regulatory requirements, they can be addressed successfully through sound pollution prevention and alternative manufacturing practices, such as those provided by innovative abrasive flow machining (AFM). Furthermore, in many cases, hand polishing is an unsuitable procedure due to the high demand for uniform roughness, uniform thickness of the removed material, adequate geometry after finishing, etc. Additionally, for many applications whole components do not need to have high integrity specifications, as the mere optimization of the material surfaces through improved integrity (roughness, texture, residual stresses, etc.) greatly enhances the properties of the materials for such applications. This is due to the fact that the majority of failures, such as fatigue fracture, fretting fatigue, wear and corrosion, etc., are very sensitive to the structure and properties of the material surface, and in most cases material failures originate from the surface. However, some research studies on the AFM of a range of materials have shown encouraging possibilities for producing (1) much thicker layers with nanostructures on the surface, (2) lower heat impact on the material surface, and (3) more compressive residual stresses on the surface (which are favorable), in combination with such processes. Thus, the ability to enhance the product through use of the AFM process, in order to obtain products with a longer fatigue life, better corrosion resistance, etc., remains a challenge with real possibilities.

Energy consumption is increasingly a key parameter that reflects the environmental burden. Understanding and characterizing task-oriented energy consumption is quite essential for exploring the potential energy savings in production management and for making robust decisions regarding the potential to improve energy efficiency (He et al., 2012). By reducing the energy requirements, the efficiency of the machining process is increased, and thus greenhouse gases can be reduced for a given machining operation (Hu et al., 2012). In general, in the finishing process electrical energy is used to perform the polishing process. The methodology for linking energy consumption with the environmental burden of machining operations has been demonstrated and proven in (Narita et al., 2008), and the energy data can thus be interpreted in the form of equivalent CO_2 emissions.

Many researchers have focused their work on optimizing energy consumption with respect to the machining conditions. A broader survey has recently been reported in (Pervaiz et al., 2013), which focuses on energy efficiency in relation to the machined surface quality. However, in most cases the optimal balance between the maximization of productivity and the minimization of production costs is sought, while the constraints are in the process itself. And it has to be emphasized that productivity and costs are in general contradictory in nature. Agudo et al., recently raised in their work (Aguado et al., 2013) that to harmonize efficiency and sustainability, environmental innovations are necessary to be implemented for transforming the traditional production systems into a sustainable systems, and add extra value to the final products. Considering AFM, the possibility of decreasing energy consumption in parallel with increasing productivity can be sought in innovative upgrades of existing processes.

Therefore, the goal of this research is to analyze surface performances and the energy efficiency of the AFM finishing process and technology. Additionally, based on new directions in clean and dry processes, this work analyzes an innovative upgrade of AFM with a movable/rotatable mandrel (AFMmm), which shows high potential to improve a) productivity, b) quality, c) environmental impact, d) energy consumption, e) operational safety, f) personal health, g) waste management, and h) manufacturing costs.

1.1. AFM

Abrasive flow machining (AFM) is actually a polishing technique (a finishing method) that uses the flow of a pressurized abrasive polymer media, passing through the workpiece, to remove workpiece material, as shown in Fig. 1 (Kenda and Kopac, 2010). AFM represents a performance enhanced process and can be used for polishing, deburring, removing recast layers, etc. (Schrader and Elshennawy, 2000). It is suitable for finishing external as well as internal surfaces, which are often complex and inaccessible. It is specifically appropriate for parts with complex geometry and high surface integrity demands. Despite its advantages, the AFM process is still not widely and generally used in real industrial finishing applications (Kenda et al., 2011). Therefore, further development is inevitable. The reason for this is, on the one hand, its high level of complexity, and on the other, the high energy demands of this process. The process is not robust, does not ensure uniform surface integrity along the machined surface, and has relatively low productivity. It has mainly been used for deburring. However, the process can be upgraded with innovative kinematics for fully controlled polishing media flow, to such a level that it will be reliable, economical, energy efficient, and ready for use in real EU

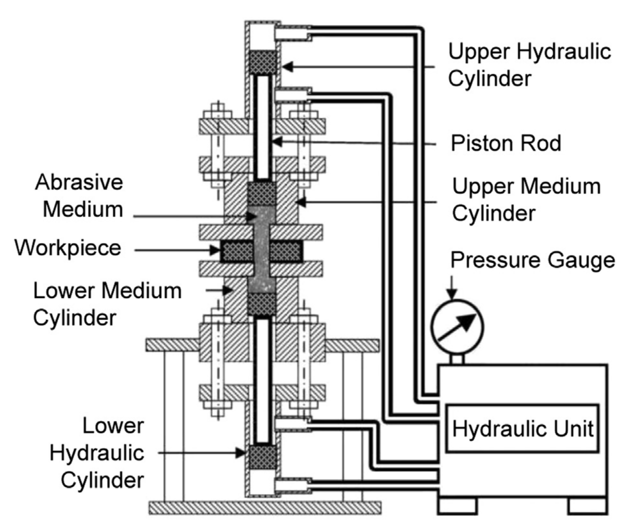

Fig. 1. Scheme of the abrasive flow machining process (AFM).

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