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Evaluation of neural models applied to the estimation of tool wear in the grinding of advanced ceramics

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A B S T R A C T

Grinding wheel wear, which is a very complex phenomenon, causes changes in most of the shapes and properties of the tool during machining, reducing the efficiency of the grinding operation and impairing workpiece quality. Therefore, monitoring the condition of the tool during the grinding process plays a key role in the quality of workpieces being manufactured. In this study, diamond tool wear was estimated during the grinding of advanced ceramics using intelligent systems composed of four types of neural networks. Experimental tests were performed on a surface grinding machine and tool wear was measured by the imprint method throughout the tests. Acoustic emission and cutting power signals were acquired during the tests and statistics were obtained from these signals. Training and validating algorithms were developed for the intelligent systems in order to automatically obtain the best estimation models. The combination of signals and statistics along with the intelligent systems brings an innovative aspect to the grinding process. The results indicate that the models are highly successful in estimating tool wear.

1. Introduction

The use of advanced structural ceramics such as aluminum oxide, silicon nitride and zirconia in engineering and medicine is gaining ground due to their low density, high wear and corrosion resistance and their ability to withstand high temperatures. These ceramics are employed in the production of bearings, seals for hydraulic pumps, valves, rotors and cutting tools, as adiabatic material for catalysts, and as artificial joints, teeth and bones (Agarwal & Venkateswara Rao, 2013; Chang & Kuo, 2007).

Grinding stands out as one of the most important stages in the machining process of this type of ceramic, because it is highly complex and involves the contact of a large number of abrasive particles with the workpiece surface, providing more precise dimensional control and excellent finish (Bianchi, Aguiar, Silva, Silva Jr., & Fortulan, 2003; Do Nascimento et al., 2015). On the other hand, the extreme hardness and brittleness associated with engineering ceramics cause high grinding forces, low material removal rate, high wheel wear, as well as surface and sub-surface damage (Emami, Sadeghi, Sarhan, & Hasani, 2014).

The result of a grinding process can be subdivided into characteristics concerning the geometry and surface integrity of a ground component. The geometrical quantities are dimension, shape and waviness, as essential macrogeometric quantities; whereas the roughness condition is the main microgeometric quantity. The surface integrity state can be described by residual stresses, hardness and structure of the material (Brinksmeier, Tönshoff, Czenkusch, & Heinzel, 1998; Miranda, Aguiar, Euzebio, & Bianchi, 2010). As more materials are removed, the form and properties of the tool are mainly changed due to the wear, which is an extremely complex process. As a result of this change, the machining operation often becomes inefficient and the quality of the machined workpiece is affected negatively most of the time (Li, Liao, O'Rourke, & McSpadden, 1997; Liao, Tang, Qu, & Blau, 2008; Warren Liao, Ting, Qu, & Blau, 2007). As the wear of the grinding wheel plays an important role in the surface quality of the ground workpiece, tool condition monitoring is of great importance for the process.

Direct and indirect methods for tool condition monitoring are used to evaluate the tool wear in grinding. The direct methods directly evaluate the tool condition using some optical sensor and require stopping the machining operations. Indirect methods rely on some sensory signals such as forces, power, vibration, and acoustic emission (AE) that correlate with the tool condition.

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They are more common because no interruption of machining operations is needed (Martins, Aguiar, Frech, & Bianchi, 2014; Sutowski & Plichta, 2006; Warren Liao et al., 2007) and, therefore, this investigation is focused on indirect method of monitoring the grinding wheel wear.

Many methods can be found for tool condition monitoring, and indirect methods that rely on the relationship between tool conditions and measurable signals (such as force, acoustic emission (AE), vibration, current, etc.) have been extensively studied. The major advantage of using AE to monitor tool condition is that the frequency range of the AE signal is much higher than that of machine vibrations and environmental noises, and does not interfere with the process (Martins et al., 2014; Zhou, Pang, Zhong, & Lewis, 2011). On the other hand, power or force signals have also been largely used in grinding researches. The signal can be monitored either by the electric current of the electric motor or by the product between voltage and current signals, which gives the electrical power consumed by the electric motor. Thus, an estimate of the cutting force can be easily obtained if a model of the electric motor is available (Aguiar et al., 2007). Also, a more expensive and precise force measuring system can be used in which is generally possible to measure three axes forces.

According to Elangovan, Devasenapati, Sakthivel, and Ramachandran, (2011), tool condition monitoring and diagnosis involves collection, processing and analysis of data related to the tool under various experimental conditions and interpreting the results to the real life applications. A variety of techniques have been employed to carry out each phase of tool condition monitoring. Such phases include, choice of the parameters to be captured, feature extraction, feature selection and feature classification. Many researchers have contributed toward condition monitoring studies that are computationally simple, yet effective and robust.

A review of the specific topic of this work will be presented in the next section instead of presenting a review on tool condition monitoring researches that used indirect methods. The reader interested in such review can check the works of Bhuiyan and Choudhury (2014), Dimla Snr. (2000), Li (2002) and Rehorn, Jiang, and Orban (2005).

In addition, this work was developed based on neural models mostly by the reasons given in the work of Mukherjee and Routroy (2012). The authors state that to implement appropriate online grinding process control mechanism, explicit functional model(s) needs to be developed by using mechanistic or data-driven empirical modeling approach. Mechanistic modeling approaches cannot consider all intrinsic process complexity manifested due to the presence of a large number of inter-acting variables. In addition, due to interdependence between various process variables, these models are found to be inaccurate in many situations. Complexity of the problem is further enhanced if there are nonlinear multiple responses to be modeled simultaneously. The authors still state that empirical models can handle such nonlinear behaviors, considering the internal complexities and dynamics of processes, where artificial neural network (ANN) is one of the empirical modeling techniques used for prediction and control of grinding processes.

This research aims at estimating the tool wear during the grinding of advanced ceramics using intelligent systems, which are composed of four types of neural networks, and it is distinguishable from other works in the following aspects: (1) the tool condition monitoring of diamond grinding wheel is performed in conventional surface grinding of advanced ceramics; (2) the use of AE RMS and power signals as well as statistics derived from these signals for monitoring the grinding wheel wear as inputs to the intelligent systems have not been found in literature; (3) tests of four types of intelligent systems are developed in which the parameters and inputs are varied in order to search for the best models, that is, the systems act as feature extraction tools; (4) Among the types of systems for wear estimation, three of them have not been tested yet for the specific topic, such as RBF, GRNN and ANFIS; and (5) comparison of the intelligent systems is performed with regard to the error and processing time, searching for the best ones for more feasible practical implementation.

2. Literature review

2.1. Ceramic machining and tool wear

Advanced ceramics possess characteristics of wear and high temperature resistance, high hardness, low thermal and electrical conductivity, and chemical stability. However, many of the characteristics that make ceramics so attractive also make them difficult to manufacture using traditional machining-based methods. Diamond tools are typically used to machine tough ceramics because diamond has excellent mechanical and thermal properties (Li, Wang, Fan, & Xu, 2007; Samant & Dahotre, 2009).

Diamond grinding is still the most effective and dominant technique in achieving the desired tolerances and surface integrity, although there are many conventional methods for ceramic machining (Agarwal & Rao, 2008; Li et al., 2007).

The tool performance plays a key role in the behavior of any grinding process. This behavior may change significantly during the grinding process, making it difficult to predict during the operation. The grinding wheel may lose its ideal conditions during its manufacturing process in addition to undergoing changes during cutting. Therefore, grinding results are directly dependent on the topographical conditions of the wheel-cutting surface. If these conditions change, the dressing operation becomes crucial, which is the process of conditioning the wheel surface to remodel it when there is excessive loss of its original shape through wear (Liang et al., 2012; Moia et al., 2015). Based on the above statements, grinding wheel conditioning monitoring is thus necessary.

According to Fathima, Senthil Kumar, Rahman, and Lim (2003), wheel wear is an extremely complex process, which involves the culmination of numerous wear events encountered between many single grits and the workpiece. The conventional way of quantifying wheel wear is to express it as volumetric loss of material, which tells little about the wear mechanism. It is generally recognized that there are three main mechanisms of wheel wear: attrition wear, grain fracture and bond fracture. Attrition wear involves dulling of abrasive grains and the growth of wear flats by rubbing against the workpiece. Grain fracture refers to removal of abrasive fragments by fracture within the grain, and bond fracture occurs by dislodging the abrasive from the binder. Still, the authors state that the end of wheel life is generally indicated by excessive forces, or by loss of finish, form, or size of the workpiece. The end of wheel life is deduced by a skilled operator, or with the help of special sensors. The wheel wear must be compensated in order to obtain high accuracy and tolerance. If the wheel is dressed prior to the end of wheel life, the wear rate will increase, and if it occurs later the workpiece surface will be affected.

The diamond grinding wheel wear can be accurately measured by a wheel print technique and then the *G* ratio (material removal volume/diamond wheel wear volume) can be obtained for ceramic grinding. Some studies demonstrate that the wear rate of diamond layer is an important parameter in ceramic grinding; it affects the material removal rate as well as the *G* ratio (Bianchi et al., 2003; Li et al., 2007).

2.2. Related works on grinding wheel condition monitoring

In this section a specific review of related works will be presented. Many researches on tool condition monitoring of various