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UNIVERSIDADE ESTADUAL PAULISTA
Faculdade de Engenharia
Campus de Bauru

FABIO ISAAC FERREIRA

CORRELATION BETWEEN ELECTROMECHANICAL IMPEDANCE AND SURFACE QUALITY OF GROUND WORKPIECES

BAURU

2020

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CORRELATION BETWEEN ELECTROMECHANICAL IMPEDANCE AND SURFACE QUALITY OF GROUND WORKPIECES

A thesis presented to the Faculty of Engineering Bauru (FEB) in partial fulfillment of the requirements for the doctoral degree (Ph.D.) in the subject of Electrical Engineering.

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Ferreira, Fábio Isaac.
Correlation between electromechanical impedance and surface quality of ground workpieces / Fábio Isaac Ferreira, 2020
83 f. : il.

Orientador: Paulo Roberto de Aguiar

Tese (Doutorado)-Universidade Estadual Paulista. Faculdade de Engenharia, Bauru, 2020

1. Grinding. 2. Electromechanical impedance. 3. Piezoelectric transducer. 4. Structural health monitoring. 5. Surface Quality. I. Universidade Estadual Paulista. Faculdade de Engenharia. II. Título.

UNIVERSIDADE ESTADUAL PAULISTA

Câmpus de Bauru

ATA DA DEFESA PÚBLICA DA TESE DE DOUTORADO DE FÁBIO ISAAC FERREIRA, DISCENTE DO PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA ELÉTRICA, DA FACULDADE DE ENGENHARIA - CÂMPUS DE BAURU.

Aos 03 dias do mês de agosto do ano de 2020, às 14:00 horas, no(a) Via sistemas de videoconferência e outras ferramentas para comunicação a distância, reuniu-se a Comissão Examinadora da Defesa Pública, composta pelos seguintes membros: Prof. Dr. PAULO ROBERTO DE AGUIAR - Orientador(a) do(a) Departamento de Engenharia Elétrica / Faculdade de Engenharia de Bauru - UNESP, Prof. Dr. FABRICIO GUIMARÃES BAPTISTA do(a) Departamento de Engenharia Elétrica / Faculdade de Engenharia de Bauru - UNESP, Prof. Dr. ROSEMAR BATISTA DA SILVA do(a) Faculdade de Engenharia Mecânica / Universidade Federal de Uberlândia, Prof. Dr. BRUNO ALBUQUERQUE DE CASTRO do(a) Departamento de Mecatrônica / FATEC - Faculdade de Tecnologia de Garça, Prof. Dr. BRENO ORTEGA FERNANDEZ do(a) Departamento de Engenharia Elétrica / Centro Universitário de Lins - UNILINS, sob a presidência do primeiro, a fim de proceder a arguição pública da TESE DE DOUTORADO de FÁBIO ISAAC FERREIRA, intitulada **CORRELATION BETWEEN ELECTROMECHANICAL IMPEDANCE AND SURFACE QUALITY OF GROUND WORKPIECES**. Após a exposição, o discente foi arguido oralmente pelos membros da Comissão Examinadora, tendo recebido o conceito final: Aprovado. Nada mais havendo, foi lavrada a presente ata, que após lida e aprovada, foi assinada pelos membros da Comissão Examinadora.

Prof. Dr. PAULO ROBERTO DE AGUIAR

Prof. Dr. FABRICIO GUIMARÃES BAPTISTA p/

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Prof. Dr. BRENO ORTEGA FERNANDEZ p/

This research work is wholeheartedly dedicated to my beloved parents, who have been my source of inspiration and gave me strength when I thought of giving up, who continually provide their spiritual, moral, and emotional support.

ACKNOWLEDGMENTS

The researcher would like to give thanks to all the persons that somehow contributed with this study.

To God for giving me the inspiration and strength to conduct this study.

To my entire family, specially to my mother Rosa, father Antonio, sister Caroline, brother Alexandre, and grandmother Lidia, for their moral and emotional support during this period.

To my advisor in Brazil, Dr. Paulo R. de Aguiar, who guided and helped me to make the study a well-done achievement, sharing his words of advice and encouragement to finish it.

To my advisor in the USA, Dr. Mark J. Jackson, for accepting me as a Research Scholar at Kansas State University, Polytechnic campus, sharing his experience and showing me different points of view.

To professors Dr. Rosemar B. da Silva, Dr. Fabricio G. Baptista, and Eduardo C. Bianchi, who contributed to make this study happen.

To all my friends and classmates who have been with me during this journey and showed me how important is the value of friendship.

To Sao Paulo State University (Unesp), which provided facilities to the electromechanical impedance measurements, to Federal University of Uberlandia (UFU), where surface grinding has been performed, and to Kansas State University Polytechnic campus (K-State), where cylindrical grinding and electromechanical impedance measurements have been conducted.

To the Blaser Swisslube, Villares Metals, Saint Gobain Abrasives for the donation of the coolant, workpiece material, and grinding wheel, respectively, and to the Advanced Manufacturing Institute (AMI) to provide the data acquisition board.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code PDSE 88881.190384/2018-01.

RESUMO

A retificação é um processo de manufatura de extrema importância para a produção de partes de alta precisão e para garantir sua qualidade superficial. Medições elétricas desempenham um importante papel em métodos de monitoramento indireto, os quais garantem a eficiência do processo. No entanto, métodos tradicionais utilizam sensores de alto custo e requerem esforços computacionais expressivos. Este estudo discute correlações entre a técnica da Impedância Eletromecânica (EMI) e parâmetros mecânicos e elétricos do processo da retificação. A técnica EMI aplicada na retificação é inédita e tem a vantagem de empregar equipamentos de baixo custo, que requerem um sistema de monitoramento mais simples, quando comparado com as técnicas tradicionalmente utilizadas. Este trabalho propõe apresentar o potencial desta técnica, a qual poderia substituir satisfatoriamente os métodos tradicionais. Dois conjuntos de testes laboratoriais foram realizados independentemente para estudar a correlação entre medições EMI e parâmetros do processo. O primeiro conjunto de testes estudou a técnica EMI aplicada na retificação plana tangencial, enquanto o segundo, na retificação cilíndrica de mergulho. Em ambos os testes, experimentos foram realizados em um ambiente controlado para isolar as variáveis de interesse e as medidas EMI foram investigadas para diversas bandas de frequências. Para a retificação plana, fortes correlações entre EMI e espessura equivalente de corte, rugosidade média, microdureza e sinais de potência foram encontradas. Para a retificação cilíndrica, correlação entre rugosidade média e os índices de dano foram obtidos. Esses resultados permitem inferir informações sobre o processo da retificação através do monitoramento indireto.

Palavras-chave: retificação, impedância eletromecânica, transdutor piezoelétricos, monitoramento da integridade estrutura, qualidade superficial.

ABSTRACT

Grinding is a machining process of utmost importance to produce high precision parts and guarantee surface quality. Several techniques have been studied throughout the years to improve the quality of workpieces manufactured by the grinding process. Electrical measurements play a key role during indirect monitoring methods which enhance the process efficiency due to the continuity of the operation by an on-line monitoring system. However, well-established methods, such as acoustic emission and vibration signals, employ high-cost sensors and require tough computational efforts. This study discusses correlations among Electromechanical Impedance (EMI) technique and mechanical and electrical parameters from grinding. The EMI technique applied in grinding is innovative and has the advantage of employing cheaper equipment and requiring a simpler monitoring system when compared to traditional techniques. This work aims to show the potential of that new technique, which can appropriately replace the traditional ones. To this end, two experimental tests sets were conducted independently to study the correlation between EMI measurements and parameters from the process. The first studied the EMI technique on surface grinding, while the second studied on cylindrical grinding. In both, tests were performed in a controlled environment to isolate the variables of interest and EMI was investigated for several frequency bands. For the surface grinding, strong correlations among EMI and equivalent chip thickness, roughness, and microhardness of the workpiece, as well as power signals were found out. The RMSD (root-mean-square deviation) index for the real part of the signature in the band 80-85 kHz showed a good correlation with roughness and power, while the CCDM (correlation coefficient deviation metric) index for the imaginary part of 50-55 kHz showed good correlation with microhardness. For the cylindrical grinding, the correlation between surface roughness and damage indices was studied and the best correlation was found to be with the CCDM index in the frequency band of 125-130 kHz. Those results allow the user to infer information about the grinding process through indirect monitoring.

Keywords: grinding, electromechanical impedance, piezoelectric transducer, structural health monitoring, surface quality.

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LIST OF ABBREVIATIONS

ADC – Analog-to-Digital Converter

a_d – Dressing Depth, µm

ae – Radial depth of Cut, µm

bw – Bandwidth, kHz

AE – Acoustic Emission

EMI – Electromechanical Impedance

C – Capacitance, F

CCDM – Correlation Coefficient Deviation Metric

DAQ – Data Acquisition

DFT – Discrete Fourier Transform

f – Frequency, Hz

FRF – Frequency Response Function

h_{eq} – Equivalent Chip Thickness, µm

MQL – Minimum Quantity Lubrication

PLB – Pencil-Lead-Break

PZT – Pb-(lead) Zirconate Titanate

q_s – Ratio of Grinding Wheel/Workspeed

Q'_w – Specific Removal Rate, mm^2/min

ρ - Pearson Correlation Coefficient

RMSD – Root-Mean-Square Deviation

R_a – Arithmetic Average Roughness, µm

R_t – Maximum difference of roughness between peak height and valley depth, µm

R_z – Arithmetic average of roughness between the highest peak and lowest valley in each sampling length, µm

SHM – Structural Health Monitoring

TCM – Tool Condition Monitoring

U_d – Overlap Ratio

USB – Universal Serial Bus

v_d – Dressing Speed, mm/s

v_f - Radial Feed Rate, mm/min

v_s – Cutting Speed, m/s

v_w – Workspeed, m/min

X_c – Capacitive Reactance, Ω

Z_1 – Impedance of the Healthy Structure, Ω

Z_2 – Impedance of the Damaged Structure, Ω

Z_E – Electrical Impedance, Ω

Z_S – Mechanical Impedance of the Structure, Ω

Z_T – Mechanical Impedance of the Piezoelectric, Ω

CONTENTS

1 INTRODUCTION

Grinding is one of the most important processes of the manufacturing chain. Parts which require tight dimensional tolerances or high surface quality must be ground to guarantee design requirements. Since grinding is one of the last processes of the chain, the parts have high added value and losses cause high economic impact (Da Conceição Junior *et al.*, 2018). However, grinding is one of the most complex machining operations because of several aspects, such as heat transfer between cutting tool and the workpiece, which can cause thermal damages (Vendrame *et al.*, 2018).

To appropriately control machining operations, monitoring of mechanical systems is widely employed by industries that seek automation and quality in their manufacturing chains. Such intelligence level in the machines is reached by smart systems that might be composed of data acquisition equipment, signal processing, computational intelligence, optimization algorithms, and/or general actuators, which can play a key role in the productivity and efficiency of production processes. Monitoring systems can be designed for different purposes, such as:

- detecting and classifying conditions and failures;
- estimating the current values for the parameters of interest to guarantee dimensional, shape, and quality requirements;
- predicting steps forward to understand the behavior of the process parameters or tool wear and lifetime;
- taking part in the decision-making process such as emergency signals for the process security, stops to replace tools, or to avoid failures.

In each situation, researches have proposed different systems and techniques to indirectly monitor the process, as will be mentioned in the next section. Those systems can be used to replace parameters measurements, which often require stops or even harm the parts, causing their losses (Boaron and Weingaertner, 2018). Consequently, reliable and non-destructive systems are desired to improve the efficiency of the operations, to decrease economical losses, to reduce idle time, and to guarantee the quality of production chain.

However, most of them propose solutions that use expensive equipment and transducers (Tinoco *et al.*, 2019), or that are still inefficient for generic configurations (Alexandre *et al.*, 2018). Systems that can effectively be employed in the field are scarce and expensive and most of them are still being tested. The challenge is to find a monitoring system which can be effectively employed on operations.

1.1 Objective

As mentioned before, several techniques and equipment have been studied to achieve better results in the processes, improving quality and productivity. However, most of them require expensive equipment, complex set-ups and high computational efforts. Therefore, the objective of the present study is to investigate the electromechanical impedance (EMI) technique, in which it will be employed a low-cost transducer, applied to surface and cylindrical grinding. This technique is innovative for grinding operation, especially for miniaturized parts, such as small camshafts, and showed promising to replace traditional methods in previous tests.

Correlations between EMI and grinding parameters were studied in a controlled environment to verify if that technique could be used to replace traditional methods. Such investigation aims at an indirect monitoring system to be developed in the next works which ensures superior surface quality of ground workpieces by using low-cost equipment. The objective of this work is to show that the technique presented here has the potential to replace the traditional expensive methods, such as acoustic emission.

1.2 Justification

The investigation about EMI measurements applied to the quality of the grinding process is innovative and shows a great potential to be an alternative to replace classical techniques, such as acoustic emission and vibration signals. The present study differs from Marchi *et al.* (2015) because they studied the burn only by visual inspection and they did not consider other important aspects related to workpiece surface integrity. Moreover, this study differs from Junior, D'addona, *et al.* (2018) because they started to investigate the EMI technique applied on the dressing operation. We have published part of the results presented here in Batista da Silva *et al.* (2018) and in Ferreira *et al.* (2019), in which EMI technique was employed in surface grinding under controlled environmental conditions. The study of correlations between EMI and input (equivalent chip thickness, workspeed, feed rate) and output (roughness, microhardness, power) grinding parameters is discussed in more details in the current research, that includes real and imaginary parts of the impedance for several frequency bands. Moreover, the camshaft grinder that was employed in the current study is used to grind miniaturized parts. Therefore, this study is important to understand the behavior of the EMI when applied to surface and cylindrical grinding and to verify feasibility of industrial employment.

5 CONCLUSIONS

In this work, the monitoring features applied to surface grinding and cylindrical plunge grinding were investigated independently. Some parameters to assess the surface integrity of workpieces and process efficiency were measured and some correlations were found with EMI measurements. The following conclusions can be drawn:

Surface grinding

- Severity of the process was correlated to damage indices and directly proportional relationships were preferable because it was adopted the hypothesis of that the greater the severity of the process, the greater the influence on the workpiece. So, the CCDM index calculated on the real part of the signatures for the frequency band of 70-75 kHz presented the best correlation with the equivalent chip thickness (h_{eq}) of the process. Such combination (CCDM real part 70-75 kHz) showed effective conditions because the same correlation was found for the parameters *ae* and v_w individually.
- Good correlations were found between h_{eq} and power, and between h_{eq} and roughness. No correlation was found between h_{eq} and microhardness.
- The best correlation between EMI measurements and power was found for the RMSD index for the real part of the impedance in the frequency band of 80-85 kHz, but this correlation requires further studies.
- The best correlation between EMI measurements and roughness was for the RMSD index for the real part of the impedance in the frequency band of 80-85 kHz. This configuration could be used to infer workpiece quality through indirect monitoring.
- The best correlation between EMI measurements and microhardness was found for the CCDM index for the imaginary part of the impedance in the frequency band range of 50-55 kHz.
- EMI technique is a good alternative to monitor surface grinding instead of using conventional techniques and has the advantage of employing low-cost PTZ diaphragms.

Cylindrical plunge grinding

- R_a roughness values increased with feed rate and workspeed, but with lesser influence of the latter. All the surface roughness values were below the upper reference limit for the grinding process, R_a = 1.6 µm.
- The surface roughness presented a correlation coefficient of 0.92 with the grinding power and noted that grinding power varied according to the severity of grinding.
- In the EMI measurements, the PZTs attached to a same sample showed differences between their signatures. The differences were quantified by the RMSD and CCDM indices calculated for the real part of the impedance, which presented a consistent result only for the CCDM index.
- Correlation between surface roughness and damage indices was studied and the best correlation was found to be with the CCDM index in the frequency band of 125-130 kHz, which resulted in a correlation coefficient of 0.92 for the PZT 1 and 0.83 for the PZT 2, respectively. That is a satisfactory result, considering that the PZT diaphragm costs less than 1 dollar while traditional monitoring systems, such as power and acoustic emission systems use very expensive equipment. These results can be improved by investigating different frequency bands with different bandwidths, or by studying other signal processing approaches for the EMI technique.

At the end, this work presented two different approaches, in which the EMI technique has been applied. For surface grinding, the RMSD index presented to be efficient to correlate EMI with power and average roughness, while the CCDM index showed efficiency to correlate EMI with equivalent chip thickness and microhardness. Frequencies from 50 kHz to 85 kHz showed to be promising to monitor the process. On the other hand, when performing cylindrical grinding, the CCDM index showed to be efficient to correlate EMI with average roughness. In this process, frequencies showed to be more promising around 135 kHz. Based on this difference, it is possible to presume that the EMI technique varies according to several features of the process, such as grinding wheel, workpiece size, steel type, etc. Therefore, monitoring based on electromechanical impedance must be individually adjusted for each application.

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