STRATEGIC ACTIONS TO IMPROVE EFFICIENCY IN CERAMIC TILE RECTIFICATION PROCESSES

Julio Serrano Mira[(1)], José V. Abellán Nebot[(1)], Gracia M. Bruscas Bellido[(1)], Luis Guaita Delgado[(2)]

[(1)]Universitat Jaume I, Castellon, Spain

[(2)] Grupo Keraben, Nules (Castellon), Spain

ABSTRACT

Ceramic tile rectification was first used on an extensive scale in the manufacturing of compact porcelain stoneware, mainly in polishing, and today, it is a widely used process in the manufacture of both polished and unpolished, medium and large-sized compact and glazed porcelain tile. Ceramic tile rectification is an extremely inefficient process with low material removal rates, which implies high energy consumption per unit removed volume, and indeed it is not uncommon for just 10-30% of the total electricity consumed to be used in the actual removal process. Furthermore, productivity and the consumption of energy and grinding tools depend closely on operating conditions. In the face of growing competition and energy costs, coupled with the increase in environmental restrictions and greater sensitivity towards process and product sustainability, the ceramic industry has made significant efforts to improve efficiency and reduce its environmental impacts, and a host of studies and applications can be found in this field. However, in regard to abrasive machining of ceramic tiles, very few studies have focused on improving efficiency in the polishing process. This paper reviews research studies that centre on abrasive machining, both at a general level, by looking at the characteristics and particularities of the process, and at the level of its application in machining metals, technical ceramics and ceramic tiles. Thus, operating and performance principles and models for this type of process are defined and the influence of operating conditions and of the control system or strategy on its efficiency, productivity and cost assessed. Having set out and analysed that information, as a conclusion, it proposes a number of actions and lines of work aimed at improving the process, so that they contribute to ceramic tile rectification becoming more productive and more environmentally and economically sustainable.

1. INTRODUCTION

Ceramic tile rectification is a machining process that uses abrasive grinding tools to remove a certain amount of material along the perimeter of a tile in order to correct its gauge (tile dimensions) and ensure the edges are truly straight and accurately perpendicular and parallel to each other. It was first applied on polished compact porcelain tiles but today, its use is fairly widespread: it is always used for both polished and unpolished tiles, especially in the case of medium and large-sized formats, and in many industries, is involved in 40% of production or even more.

Abrasive machining is a forming process that involves removing material, generally in a very inefficient manner. However, in the field of the ceramic tile-manufacturing industry, it is very seldom the subject of assessment or research in the literature as an area of improvement to reduce environmental impact and improve the industry's sustainability. For example, a number of recent papers, such as Gabaldón-Estevan et al. [1], look at how European environmental and regulatory issues in this matter are affecting the industry in Spain. Their study encompasses the process as a whole, without specifically looking at polishing and grinding. The same happens in the work of Almeida et al. [2], who study the environmental profile of ceramic tiles produced in Portugal based on a life cycle assessment from the extraction of raw materials to final disposal and proposes improvement measures to reduce the impacts it finds, but again makes no reference to abrasive processes. In a third example, again no mention is made in the interesting study carried out by Ibáñez-Forés et al. [3], which presents a method of identifying the most suitable BATs (Best Available Techniques) to make the ceramic tile manufacturing process more sustainable, proposing various options that improve the environmental and economic costs of the process. Thus, the only study found that deals with the environmental impact and/or sustainability of the ceramic tile industry including its machining processes is the one by Ciacco et al. [4], in which the industry's consumption of energy in Brazil is assessed and compared in two cases: one in which bodies are formed with dry-milled material, and one where they are formed with wet-milled material. In this paper, in the case of wet milling, the calculation includes the rectification stage, which, as shown in Figure 1, accounts for 2.1% of total electricity consumption (around the same magnitude as power consumption assigned to the sorting-packaging-palletising stage and slightly lower than internal transport). This result comes from allocating electricity consumption of 437 kJ/m^2 to rectification out of a total for the process of 20.71 MJ/m^2, although previous research in this matter by the authors showed that the rectification process usually accounts for higher consumption, specifically between 50% and 100% higher than indicated by Ciacco et al.

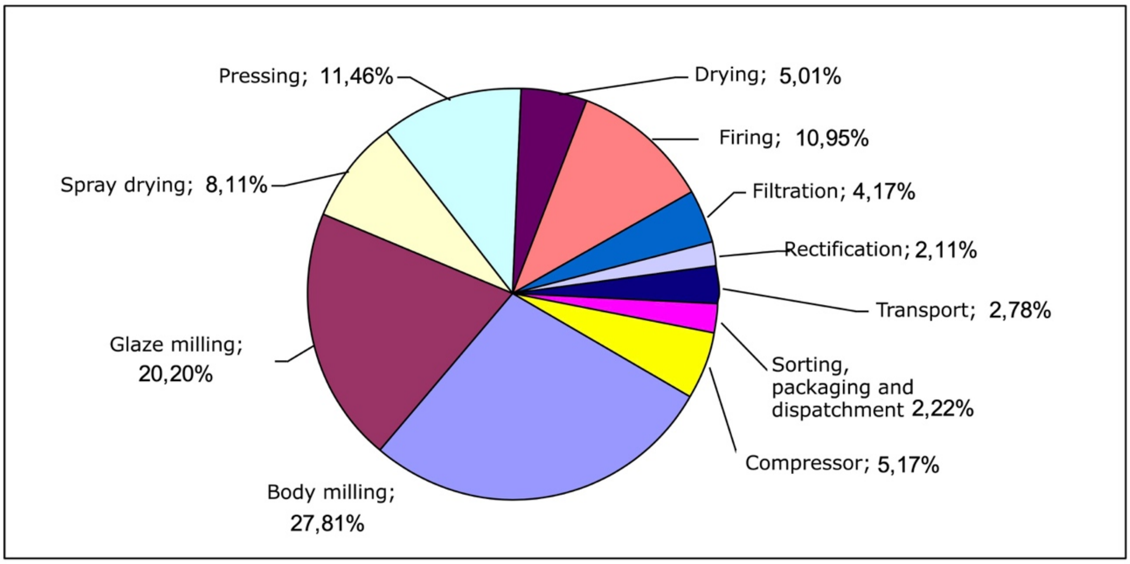

Figure 1. *Distribution of power consumption in a ceramic tile manufacturing company using wet milling in Brazil (obtained from data provided in [4])*

Focusing on the abrasive machining process in the ceramic tile industry, a number of studies can be found that deal only with the tile polishing process, without including the tile rectification stage, which has quite different characteristics in terms of procedure and tools, as these exhibit a different configuration. The polishing process is basically frontal, on the surface of the tile and the final objective is not to remove a large amount of material but to improve surface quality, i.e. to obtain high gloss. However, outside the ceramic industry, a numerous research papers have addressed the question of improving the efficiency and sustainability of both conventional and abrasive machining processes and have contributed valid concepts and solutions for general and specific processes involving conventional and abrasive machining.

The work presented here reviews published studies on abrasive machining, both at a general level in terms of the characteristics and particularities of the process, and in its application in machining metals, technical ceramics and ceramic tiles. The intention is to determine the operating principles and behaviour models for such processes and analyse how operating conditions and the control system or strategy influence their efficiency, productivity and cost. Having presented and analysed all the data, the outcome intends to propose lines of work and specific actions that should be followed to improve the process and contribute to more productive and more environmentally and economically sustainable ceramic tile machining.

2. ABRASIVE MACHINING IN THE CERAMIC TILE INDUSTRY

The process of polishing ceramic tiles has been the subject of numerous studies that individually focus on its different aspects. Assessing the results of the polishing process in terms of resulting tile roughness and gloss was the purpose of a number of papers, such as Orts et al. [5], in which the aforementioned aspects were correlated to grinding tool wear as a function of grain size in polishing lines in industrial facilities. Looking further at the same aspects, Hutchings et al. [6] complemented the study with the use of a purpose-built tribometer that allowed greater freedom when establishing different work parameters. Similarly, Olenburg et al. [7] also focus their work on looking at how roughness and gloss evolve on ceramic tiles after polishing, but in this case, they delve more deeply into aspects such as the curvature radius and wear speed on abrasive grinding tools, removal rates and energy consumption.

On a different key, some studies aim at developing models of kinematics and movement for grinding tools based on simulation, as an aid in helping to estimate roughness and, therefore, gloss of the end tiles. In this area, Sousa et al. [8] propose a simulation model based on the time that each grinding tool removes material from each area of the tile and then, by using iso-parametric equations, they estimate the end gloss obtained. Subsequently, based on these earlier studies, the same authors [9] propose modifying the transverse oscillating movement of the grinding heads to obtain better results.

Numerous studies concentrate on identifying optimal grinding tools to use for machining metals, technical ceramics and as cutting discs, in which the main characterisation criteria are the type of abrasive, grain size, grade (hardness), structure (closed, open) and type of binder, for which standards set out requirements for their designation, such as those established by UNE-EN 12413+A1:2014 standard "Safety requirements for bonded abrasive products" (Figure 2). In the case of grinding tools for abrasive machining used in the polishing of ceramic tiles, a number of authors have studied their characterisation [10], which is important since, unlike the sectors mentioned above, no standard exists that establishes specifications for these grinding tools.

Prefijo de ident. fabric. (Optativo) **xx**	1 Tipo de abrasivo **A**	2 Tamaño de grano **46**				3 Grado **K**		4 Estructura (Optativo) **8**		5 Aglomerante **V**	6 Sigla o clave del fabricante **x**
		Grueso	Medio	Fino	Finísimo	DEFG	Muy blanda	Compacta o cerrada	Porosa o abierta	**V**itrificado o cerámico	
	Alundum	10	30	70	220						
	Carborun-dum (CSi)	12	36	80	240	HIJK	Blanda	1	9	**B**aquelita (Resinoide)	
		14	46	90	280			2	10		
	K Corindón natural	16	54	100	320	LMNO	Media	3	12	**BF** (Resinoide + fibra refuerzo)	
		20	60	120				4	14		
		24		150		PQRS	Dura	5	16		
	Nitruro de **B**oro cúb.			180				6		**E**lástico	
						TUVW-XYZ	Durísima	7		**M**etálico	
	Diamante							8		**S**ilicato	

Figure 2. *Scheme for defining abrasive tools according to standard UNE-EN 12413+A1:2014*

3. ABRASIVE MACHINING. EFFICIENCY AND SUSTAINABILITY

This section discusses the particular characteristics of abrasive machining processes from the viewpoint of efficiency and sustainability. To do so, their characteristics are explained in detail according to three aspects: process characterisation, sustainability indicators, and process monitoring/control.

3.1. PROCESS CHARACTERISATION

Abrasive machining is a very inefficient process with low material removal rates, high energy consumption per unit removed volume, meaning that only 10-30% of electricity consumed relates to the removal process [11]. As highlighted in the paper published by Park et al. [12], these processes are an important area to work on in order to improve energy efficiency in manufacturing processes, because, as the aforementioned study points out, abrasive grinding has very poor energy efficiency, in which a small percentage of energy is used to break the chemical bonds between the particles of material.

The specific energy of any abrasive machining is defined in [13] as the cutting power required to remove shavings per volume removed material:

$$e_c = \frac{F_c \cdot V_c}{\xi}$$

where F_c is the cutting force, V_c the cutting speed, and ξ the shaving removal rate. For a particular grinding tool, the specific energy depends primarily on the maximum thickness of the shavings removed, h_{max}, and its influence can be modelled, as indicated in [14], by:

$$e_c = \frac{A}{h_{max} + B}$$

where A and B are constant. The influence of h_{max} on specific energy is known to be much greater than the type of particle size or binder used in the abrasive, so that the cutting conditions for the operation that define shaving thickness are critical to improving the efficiency of the process [14]. On the other hand, specific energy is related to the shaving removal mechanism, so that when h_{max} is low, the ductile flow mechanism prevails, whereas when h_{max} is higher, the brittle fracture mechanism prevails [14]. Figure 3 shows an example of how specific rectification energy evolves depending on the thickness of the shaving removed in the case of an alloy steel.

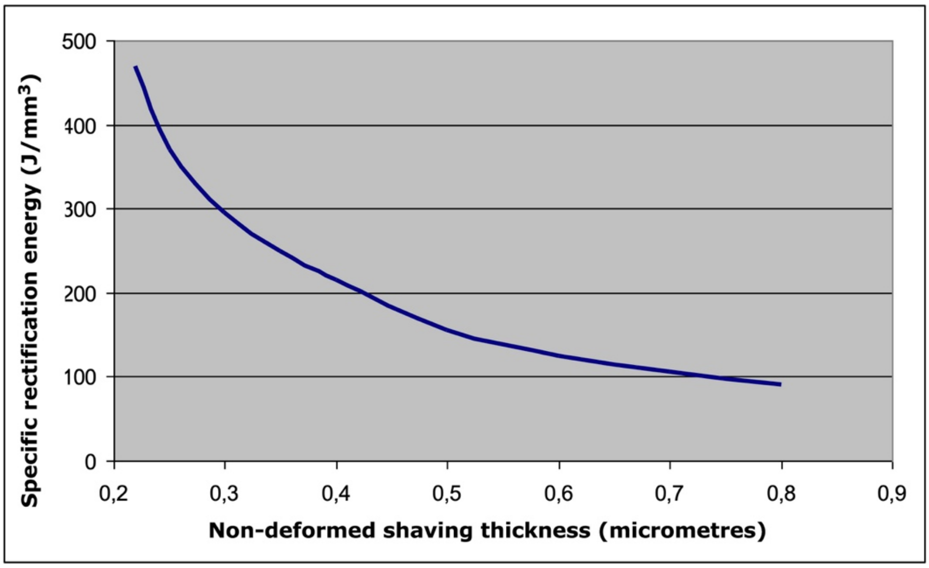

Figure 3. *Influence of maximum thickness of removed shaving, h_{max}, on the value of specific machining energy in the case of an alloy steel*

It is interesting to note that specific energy also depends on the work method used. Thus, [13] shows that in the machining of AISI 4140H (42 CrMo4) steel, down-grinding calls for higher specific energy than up-grinding, due to the higher temperatures involved in up-grinding the workpiece.

Specific energy is also clearly influenced by the cutting speeds applied. In this sense, the use of high-speed rectifiers over conventional rectifiers is seen to produce a gain in energy efficiency of between 20-30% and 50-60% when machining Inconel with CBN (cubic boron nitride) tools and switching cutting speeds from 20-50 m/s to 110-140 m/s [15].

Nevertheless, one of the problems that is still lying on the testbed today is the difficulty of choosing the correct abrasive tool for a particular application [16]. As a result, research studies that attempt to characterise the performance of different abrasive tools in order to enable proper selection for the application in question are commonplace. Study [14] examines the performance of high-speed machining on 3 types of technical ceramics, alumina, silicon nitride and zirconium using sintered diamond tools with two different particle sizes. The different shaving removal mechanisms that are produced according to the type of rectified ceramic were analysed, and forces, power ratings, specific energy and final roughness were analysed and found to be different in each of the ceramics studied. The main result was that high-speed machining is possible in technical ceramics with acceptable results in terms of quality and energy consumption.

In [13], the improvement to the process in terms of specific energy consumed was analysed when an abrasive tool with a low-density abrasive grain pattern was used that would ensure only a small number of grains were in contact with the piece during machining, thus increasing shaving thickness and reducing friction and thermal deformation in the workpiece.

Numerous studies seek to optimise cutting conditions in an abrasive machining process in terms of productivity and quality. Indeed, [17] studies the rectification of silicon carbide parts with a sintered diamond grinding tool wheel, modelling the process and optimising different objective functions (material removal rate and surface quality) using genetic algorithms. In [18], the cylindrical machining of stainless steel is modelled and optimised with respect to surface quality and vibration, using the surface response method for the model and genetic algorithms for the optimising.

Apart from its energy inefficiency, abrasive machining has a significant environmental impact due to the high use it makes of cooling lubricants. Once again, numerous research papers have proposed the use of MQL (Minimum Quantity Lubrication) systems as alternatives to machining with high consumption levels of lubricant or dry grinding, which generates excessive wear and high temperatures on the rectified parts, producing significant burns or thermal deformation. Tawakoli et al. [19] studied the influence of the abrasive tool and type of coolant/lubricant used on the performance of near-dry, MQL machining systems. Three types of conventional grinding tools made of corundum and a CBN tool were tested with up to eleven different types of lubricants in MQL (mineral oil, synthetic oil, esters, pure water, etc.) and quite interesting results were obtained in terms of the relationship between efficiency and the type of lubricant and grinding tool used in each case.

In [20], the influence of different parameters of MQL systems is studied, such as lubricant flow, air pressure or distance from the nozzle to the surface, in regard to cutting forces and the surface roughness obtained. The process is modelled using response surfaces so that optimal MQL parameters that minimise cutting force and roughness can be assessed.

3.2. SUSTAINABILITY INDICATORS

As noted above, the specific energy in abrasive machining processes is 5 to 20 times higher than in conventional machining processes such as milling and turning [13], and in many cases, the specific energy required by the spindle for machining is just 10% to 20% of the total energy consumed during the process [13]. Therefore, although specific energy is an effective indicator of the process' environmental impact, very often, over 70-80% of consumption is due to consumption at no load or by auxiliary equipment [11]. Figure 4 depicts consumption monitoring in one of the motors of a ceramic tile rectification line working under light/medium conditions, which shows that the current consumed by the motor at no load is 75.5% of the energy consumed when loaded (5.11A vs. 6.76A), a figure that increases to 82% when compared to average consumption (6.24A), which takes into account periods it stands idle between tiles. The latter figure would increase slightly if the consumption of all auxiliary equipment (tile traction systems, cooling pumps, etc.) were added together.

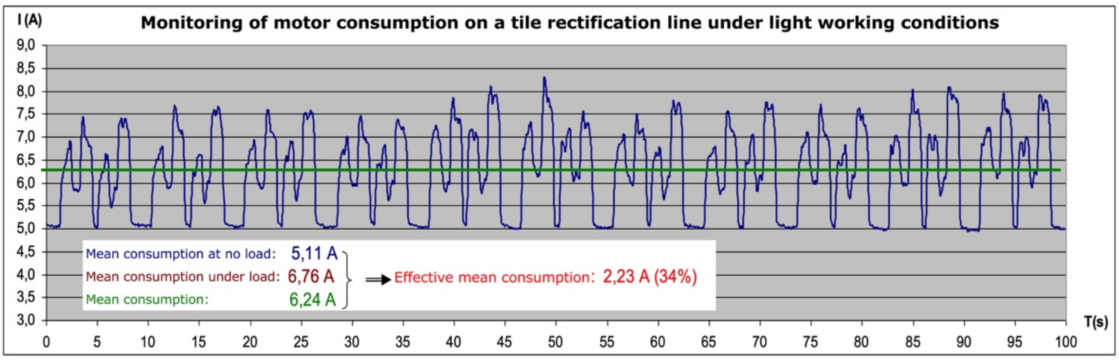

***Figure 4**. Monitoring of consumption by a motor on a ceramic tile rectification line working under light/medium load conditions, where consumption at no load represents 75.5% of consumption under load and effective mean consumption is 34%.*

To assess the sustainability of the process properly, a detailed study based on the LCA (Life Cycle Assessment) method is required. However, some authors [11] indicate that the use of the LCA method calls for the acquisition and analysis of a great deal of data, and needs to be performed by experts in the field of environmental impact analysis, all of which involves accessing expensive databases, etc. Therefore, the literature includes numerous studies on sustainability indicators that enable abrasive machining processes to be assessed more easily. A reference paper in this respect comes from Linke et al. [21], who define a series of indicators of simple sustainability applicable to any individual manufacturing process and distinguish indicators for different realms: environmental (energy, water, non-recyclable materials, airborne emissions, etc.), economic (productivity, costs, etc.) and social (labour, toxicity, etc.). The method described attempts to define a set of standard indicators that are brought together with proportional weighting to obtain an overall sustainability index that can be used to compare the sustainability of different processes. The work presented here applies the same method to assess the sustainability of a machining process and compares the results when a conventional grinding tool is used compared to a superabrasives grinding tool.

In other studies, instead of evaluating a broad sustainability index with many factors, sustainability is analysed by considering the critical aspects of the process at production level, such as surface quality and energy costs. For example, [11] defines a process sustainability index that is a function of the surface roughness obtained, the target roughness, the energy consumed, and the target energy consumption, all affected by weighting factors. This sustainability index is applied to a rectification process using two different tools, one with a vitrified binder and the other with resin, with the result that, depending on whether the object to be minimised is the roughness or specific energy, the binder to be used differs.

3.3. PROCESS MONITORING/CONTROL

In abrasive machining processes, the influence of the state of the abrasive tool on the specific energy of the process and, above all, on the final geometric quality of the workpiece has led researchers to propose systems to monitor the process and undertake corrective/preventive measures at precisely the right time. In the literature, one can find important states of the art published on the monitoring of the state of the tool in abrasive machining processes, of which [22] is one example.

The monitoring systems used mainly centre around a metering system based on some type of sensor, the most common being power sensors (clamp meters or similar devices), dynamometers, accelerometers, thermocouples to measure temperature, and acoustic emission sensors used to detect microcracks in aircraft structures or similar and used here to detect the state of the grinding tool [23]. After the measuring system, a signal conditioning and treatment system is used, where useful data is extracted from the readings to estimate the status of the process. At this point, the development of suitable descriptors of the readings is required to correlate with the state of the process. For example, the mean, the square root of the arithmetic mean, the kurtosis, etc. are all commonly used. Finally, an analysis of the historical data is required so that a model based on these newly-defined descriptors can be estimated that provides a mathematical relationship between the process parameters (cutting conditions), descriptors of the measured signals, and the variables to be estimated, e.g. surface roughness of the workpiece, state of the cutting tool (classification of its state as new, semi-new, worn), or even estimates the level of wear in microns.

Numerous studies in the field of abrasive machining have proposed monitoring systems based on some kind of on-line measurement. One interesting paper is [24], which proposes a portable system for monitoring rectification, in which a clamp ammeter is used to measure online the power consumed by the machine tool together with modular software, which handles the part of acquiring data, extracting descriptors, and analysing the current state of the grinding tool.

Apart from monitoring the state of the tool, a natural action that follows on from that is to monitor and adapt the process to its current state, thus optimising the process in terms of final product quality, energy efficiency, tooling costs, etc. Paper [25] provides details of an initial study of a control system on a ceramic rectification line to improve process efficiency by varying the conditions of each grinding tool based on measuring the electric current in each motor, so that each grinding tool on a rectification line operates under its target conditions, which is highly complex, because the operating conditions of a grinding tool are influenced by the conditions surrounding it, so that a fuzzy logic-based control system has to be used. In Figure 5, an example of this monitoring system is shown for a 16-head rectification line, in which a target operating intensity of 7.8 A for each head has been set. One can see how, in the initial state (manual adjustment without monitoring), consumption by many of the heads is outside the target range but the monitoring system enables adjustments to be made to the various heads to bring consumption in line with the target. Such adjustment is particularly complex, since altering the operating conditions of a head affects the heads around it, so the system predicts behaviour and proposes the adjustments to be made.

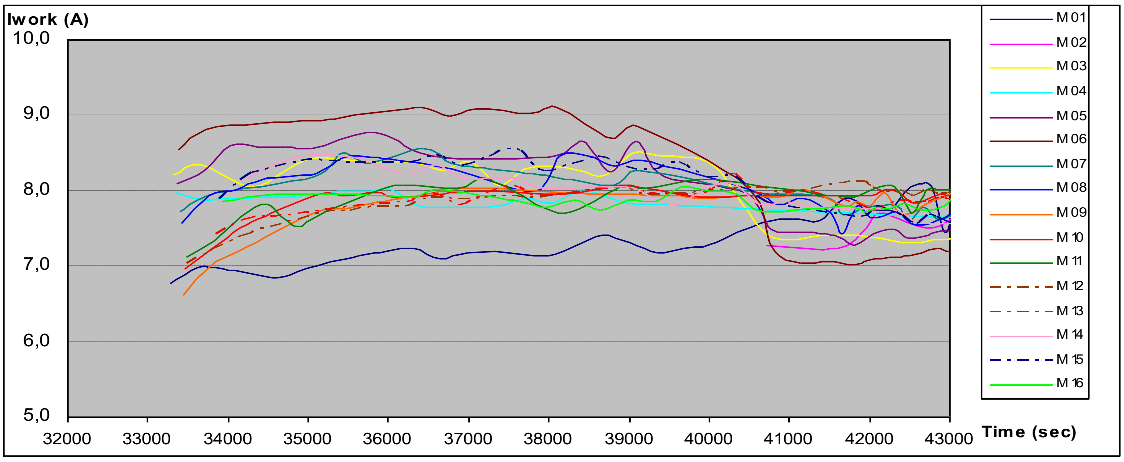

Figure 5. *Motor consumption monitoring system for a 16-head ceramic tile rectification line, showing the process to adjust the heads to ensure all of them work at the target consumption level of 7.8 A.*

4. WORKING GUIDELINES TO IMPROVE CERAMIC TILE RECTIFICATION PROCESSES

Having outlined and analysed all the above information, the conclusion is that, unlike the case of abrasive machining of metals and technical ceramics and to a much lesser extent the polishing of ceramic tiles, ceramic tile rectification has been the subject of very few research papers. Based on other abrasive machining processes, it can be said to be a highly energy-inefficient procedure and therefore a candidate for improvement both in the process itself and in production strategies. Therefore, a list of what, in the opinion of the authors, the main lines of work should be when seeking to improve the process is given hereunder with the hope that they may contribute to achieving more productive and more environmentally and economically sustainable ceramic tile rectification.

Thus, the lines of action towards which technical and research work should be directed are as follows:

- Characterisation of grinding tools and definition of a standard for naming and identifying abrasive tools, so that the features and characteristics of products offered by different manufacturers can be made more uniform.
- Currently, in wet tile rectification, water jets are used as the cutting fluid. However, our review of research papers shows that other lubrication techniques, such as MQL, and the possible use of other cutting fluids should be explored, as they have demonstrated greater efficiency under certain circumstances.
- Studies and models of the shaving removal process depending on the characteristics of the abrasive and the operating conditions need to be made and linked to the specific energy required to perform removal.
- Studies should be carried out to determine the influence of operating conditions and the characteristics of the tools on their wear and on energy consumption.
- When the above studies have been performed, operating strategies for rectification lines should be proposed, such as selecting the number of active grinding heads according to process requirements, abrasive sequences, and definition of cutting conditions.
- Specific indicators of process sustainability should be established, including a wide range of influential parameters, such as noise, social aspects, etc., in addition to the usual ones relating to cost, energy efficiency and wastage.
- Further progress must be made on developments aimed at re-using waste; so far, some work has begun in regard to waste from the polishing process, but the spectrum must be expanded to include rectification waste.
- Monitoring, controlling and adjusting abrasive machining processes is relatively complex, and some research papers have looked at applying artificial intelligence techniques and fuzzy logic, one of which focuses specifically on ceramic tile rectification. In this sense, it would be beneficial to advance in applying such techniques to the control of this type of process.

5. CONCLUSIONS

This paper has undertaken a review of research studies that assess the environmental impact and improve the sustainability of ceramic tile manufacturing and of the abrasive machining used in that process. Given the scarcity of studies dealing with abrasive tile rectification, a review was made of papers relating to abrasive machining in other areas, and the conclusion is that the process is highly inefficient (in both energy and economic terms) and calls for a profound knowledge of it in order to set correct processing conditions and improve its effectiveness.

Likewise, practically no studies have been found that deal with ceramic tile rectification, except for monitoring and control. Therefore, a series of guidelines have been proposed in regard to the direction that future lines of work should take in the field of ceramic tile rectification to improve its efficiency and sustainability.

As indicated in a few papers on abrasive machining in other fields, proper selection of the abrasive tool is fundamental for the process' efficiency, which is why an appropriate standardisation of the characteristics of grinding tools, an adequate knowledge of shaving removal mechanisms and of grinding tool wear depending on cutting conditions would all improve the productivity and efficiency of the process.

6. ACKNOWLEDGEMENTS

This study has been funded by Universitat Jaume I under project UJI-A2018-17 "Characterisation of the Ceramic Tile Rectification Process Oriented towards Improving its Productivity and Sustainability".

7. REFERENCES

[1] D. Gabaldón-Estevan, E. Criado, E. Monfort, The green factor in European manufacturing: A case study of the Spanish ceramic tile industry, J. Clean. Prod. (2014). doi:10.1016/j.jclepro.2014.02.018.

[2] M.I. Almeida, A.C. Dias, M. Demertzi, L. Arroja, Environmental profile of ceramic tiles and their potential for improvement, J. Clean. Prod. (2016). doi:10.1016/j.jclepro.2016.04.131.

[3] V. Ibáñez-Forés, M.D. Bovea, A. Azapagic, Assessing the sustainability of Best Available Techniques (BAT): Methodology and application in the ceramic tiles industry, J. Clean. Prod. (2013). doi:10.1016/j.jclepro.2013.01.020.

[4] E.F.S. Ciacco, J.R. Rocha, A.R. Coutinho, The energy consumption in the ceramic tile industry in Brazil, Appl. Therm. Eng. (2017). doi:10.1016/j.applthermaleng.2016.11.068.

[5] M.J. Orts, E. Sánchez, J. García-Ten, M.J. Ibáñez, J. Sánchez, C. Soler, J. Portoles, Comportamiento del gres porcelánico durante la operación de pulido, Bol. Soc. Esp. Cerám. Vidrio, 40 [6] 445-453 (2001).

[6] I.M. Hutchings, K. Adachi, Y. Xu, E. Sánchez, M.J. Ibáñez, M.F. Quereda, Analysis and laboratory simulation of an industrial polishing process for porcelain ceramic tiles, Journal of the European Ceramic Society 25 (2005) 3151–3156.

[7] A. Olenburg, J. C. Aurich, F. J. P. Sousa, Proceso de pulido de baldosas cerámicas – influencia del desgaste de las muelas sobre el brillo, Qualicer 2014 (2014), Castellón (Spain).

[8] F. J. P. Sousa, W. L. Weingaertner, O. E. Alarcon, Simulación computacional del proceso de pulido de gres porcelánico, Qualicer 2008 (2008), Castellón (Spain).

[9] F. J. P. Sousa, D. S. Hosse, J. C. Aurich, M. Engels, W. L. Weingaertner, O. E. Alarcon, Simulation and analysis of an alternative kinematics for improving the polishing uniformity over the surface of polished tiles, Bol. Soc. Esp. Ceram. V. 49, 4, 247-252 (2010)

[10] M.F. Gazulla, M.P. Gómez, M. Orduña, M. Rodrigo, Caracterización de muelas abrasivas utilizadas en la etapa de pulido del gres porcelánico, Qualicer 2010 (2010), Castellón (Spain).

[11] P.C. Priarone, Quality-conscious optimization of energy consumption in a grinding process applying sustainability indicators, Int. J. Adv. Manuf. Technol. 86 (2016) 2107–2117. doi:10.1007/s00170-015-8310-9.

[12] C.W. Park, K.S. Kwon, W.B. Kim, B.K. Min, S.J. Park, I.H. Sung, Y.S. Yoon, K.S. Lee, O.H. Lee, J. Seok, Energy consumption reduction technology in manufacturing - A selective review of policies, standards, and research, Int. J. Precis. Eng. Manuf. (2009). doi:10.1007/s12541-009-0107-z.

[13] J.C. Aurich, M. Carrella, M. Steffes, Evaluation of abrasive processes and machines with respect to energy efficiency, in: 19th CIRP Int. Conf. Life Cycle Eng., Berkeley, 2012.

[14] J. Chen, J. Shen, H. Huang, X. Xu, Grinding characteristics in high speed grinding of engineering ceramics with brazed diamond wheels, J. Mater. Process. Technol. 210 (2010) 899–906. doi:10.1016/j.jmatprotec.2010.02.002.

[15] C.W. Dai, W.F. Ding, Y.J. Zhu, J.H. Xu, H.W. Yu, Grinding temperature and power consumption in high speed grinding of Inconel 718 nickel-based superalloy with a vitrified CBN wheel, Precis. Eng. 52 (2018) 192–200. doi:10.1016/j.precisioneng.2017.12.005.

[16] B.S. Linke, Review on Grinding Tool Wear with Regard to Sustainability, J. Manuf. Sci. Eng. Trans. ASME. 137 (2015) 0–37. doi:10.1115/1.4029399.

[17] S. Agarwal, Optimizing machining parameters to combine high productivity with high surface integrity in grinding silicon carbide ceramics, Ceram. Int. 42 (2016) 6244–6262. doi:10.1016/j.ceramint.2016.01.008.

[18] R. Rudrapati, P.K. Pal, A. Bandyopadhyay, Modeling and optimization of machining parameters in cylindrical grinding process, Int. J. Adv. Manuf. Technol. 82 (2016) 2167–2182. doi:10.1007/s00170-015-7500-9.

[19] T. Tawakoli, M. Hadad, M.H. Sadeghi, A. Daneshi, B. Sadeghi, Minimum quantity lubrication in grinding: Effects of abrasive and coolant-lubricant types, J. Clean. Prod. 19 (2011) 2088–2099. doi:10.1016/j.jclepro.2011.06.020.

[20] M. Hadad, An experimental investigation of the effects of machining parameters on environmentally friendly grinding process, J. Clean. Prod. 108 (2015) 217–231. doi:10.1016/j.jclepro.2015.05.092.

[21] B.S. Linke, G.J. Corman, D.A. Dornfeld, S. Tönissen, Sustainability indicators for discrete manufacturing processes applied to grinding technology, Trans. North Am. Manuf. Res. Inst. SME. 41 (2013) 610–619. doi:10.1016/j.jmsy.2013.05.005.

[22] H.K. Tönshoff, T. Friemuth, J.C. Becker, Process monitoring in grinding, CIRP Ann. - Manuf. Technol. 51 (2002) 551–571. doi:10.1016/S0007-8506(07)61700-4.

[23] T. Warren Liao, Feature extraction and selection from acoustic emission signals with an application in grinding wheel condition monitoring, Eng. Appl. Artif. Intell. 23 (2010) 74–84. doi:10.1016/j.engappai.2009.09.004.

[24] Y.B. Tian, F. Liu, Y. Wang, H. Wu, Development of portable power monitoring system and grinding analytical tool, J. Manuf. Process. 27 (2017) 188–197. doi:10.1016/j.jmapro.2017.05.002.

[25] L. Prades-Martell, J. Serrano-Mira, R. Sanchis Llopis, Design and implementation of a monitoring and control system for setting and balancing a tile grinding line, Procedia Eng. 63 (2013) 252–260. doi:10.1016/j.proeng.2013.08.222.