LIFECYCLE MODELLING OF AN INNOVATIVE DURUM WHEAT DEBRANNER

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ABSTRACT

Debranning is a very common technique in the grinding process of many cereals. It has the aim of removing part of the outer layers from the kernels prior to the milling process, improving production yield and product refinement. Debranning is performed using specific machines with vertical configuration. They consist of a cylindrical perforated stator and of several rotating grinding wheel arranged in series. This study focuses on the substitution of the silicon carbide grinding wheels, traditionally used in debranning systems, with innovative diamond wheels. We exploited a set of key performance indicators (KPIs) to compare the two alternatives and to develop a life-cycle model of the diamond wheels. This model allowed to obtain some important technical and economic findings, and demonstrated that diamond wheels have potential to provide more effective results compared to the traditional wheels, from both the economic and reliability perspective.

Keywords: life-cycle modeling, debranning, diamond wheels, wheat milling

1. INTRODUCTION

Wheat kernel structure, as shown in Figure 1, consists of three essential constituents: bran, endosperm and germ. Endosperm, the major constituent, contains mainly starch granules embedded in a protein matrix and accounts for 81–84% of the grain. Germ contains the embryo and the scutellum and accounts for 2–3% of the grain. Bran, which forms 14–16% of the grain, consists of all outer layers including the aleurone layer, which is usually removed along with the other bran layers during milling (MacMasters, Bradbury, & Hinton, 1964).

Debranning is a well-established technology in the processing of bracted cereals as rice, oat and barley (Dexter and Wood, 1996). This process, in fact, effectively removes only the outer hull layers of the covered grains, allowing the recovery of intact kernels that will be differently processed in successive stages. Durum wheat debranning aims to the sequential and controlled removal of the outer layers of cereal kernels to a desired level prior to milling, thus simplifying the milling process itself, since less bran remains in the kernel to be removed during milling (Mousia et al. 2004). To facilitate the separation of the outer layers, the debranning is usually preceded by humidification operations, with the addiction of small amounts of water.

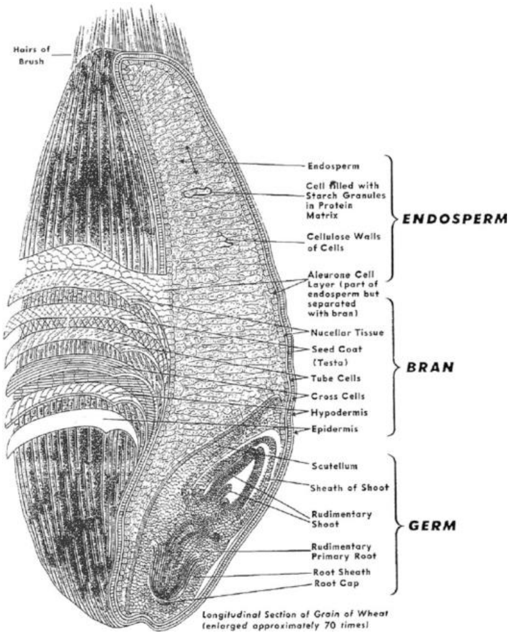

Figure 1 - Typical wheat kernel structure and composition (published on line by North America Millers' Association).

Increasing number of industrial and research studies (Dexter et al., 1994; Dexter & Sarkar 2004; Fellers, Mossman, Johnston, & Wheeler, 1976; McGee, 1995; Sekon, Singh, & Singh, 1992) reports the advantages of debranning prior to milling.

- It improves the yield and refinement of semolina in durum wheat milling, as the quantity of bran that contaminates the product will be significantly lower (Bass 1988, Dexter and Sarkar 1993);
- It ensures a higher chemical safety of the products, as the main contaminants rate is contained in the bran layers (e.g. mycotoxins) (Wilson, 2000);
- It can lower capital investment because mill flow is shortened (it needs less break and separation phases) (Dexter and Sarkar, 2004);
- It speeds up the hydration process of grain prior to the milling phase, as without the pericarp layers, the water penetration is faster and more homogeneous (Hemery et al. 2007).

Debranning is performed using particular machines with vertical configuration, consisting of a cylindrical perforated stator and of several rotating grinding wheel arranged in series. The kernels can be fed from below or above and pass through the space between the rotor and the stator. The abrasion is due to the rubbing of the grains against the walls of the machine (wheels and stator) and against other grains. Internal air pressure helps the removal of by-products through the screen (the perforated stator). As mentioned, the wheels are arranged in series vertically and can be in a variable number.

Usually, the grinding wheels are made of silicon carbide. The main limitations of this type of machine are often exactly due to the mineral nature of this material, and consequently to its poor reliability and short life-cycle. A recent technology suggests the substitution of these traditional wheels with a new kind of grinding wheels, with a thin surface deposition of synthetic diamonds on a metallic layer. The diamonds size varies with a given distribution around a particular value guaranteed by the manufacturer. This kind of modification, which could seem minimal, can lead to a longer useful-life of the device, with a more controllable process.

The aim of the study is to derive a lifecycle model that could describe the performance of diamond grinding wheels over time. Moreover, some comparisons with the silicon carbide wheels will be made, taking into account both the operational and economic points of view.

All the debranners and devices used for the tests described in this paper were provided by OCRIM S.p.A., an Italian company that acts as a world-wide leading plant producer for the milling sector. The company supported us in this study as it was interested in investigating the performance improvement achievable with the new technology, to ponder the adoption of this solution to its machines.

2. MATERIALS AND METHODS

The experimental tests were conducted partially at the Department of Industrial Engineering of the University of Parma (Italy) and partially at a production site, a Durum wheat mill sited in North Dakota (USA). The mill is equipped with two debranning machines, each one with 7 grindstone wheels. One of the debranning machines was equipped with the traditional silicon carbide package, while in the other the two lower wheels, more subjected to wear, were replaced with the innovative diamond wheels (Figure 2). This was a compromise solution: it is easy to realise that diamond wheels are more expensive than traditional ones, and then they were used only in the critical areas of the machine, for economic reasons.

The debranning rate that can be obtained is mainly a function of the power absorption of the machine. By regulating the energy absorption of the wheels, the employee can determine the product level inside the machine, and thus, at a constant global wheat flow-rate, the residence time and the debranning rate.

The evaluation of the debranning performance was carried out taking into account two KPIs, referring to the efficiency in removing bran from the kernels and to the wear over time of the wheels.

- The first KPI (KPI1) is termed “Debranning Ratio” and is computed as the ratio between the global processed mass of wheat and the relative separated mass of bran;
- The second KPI (KPI2), called “Wear Index”, is an indicator of the wear of the wheels, calculated via image analysis. A digital microscope was used to collect a sequence of pictures, from which it was possible to find out the size distribution of the diamonds and the average coverage of the surface of the wheels.

Figure 2 - 3D rendering of the grindstone package with 2 diamond wheels.

To compute the two KPIs, and to build up a life-cycle model for the new diamond wheels, we planned and implemented an important experimental campaign. A total of five measuring interventions took place at the test milling plant over a period of 26 months.

The wheels packs of the two machines were installed together in January 2014. The first measurement campaign was made immediately after the installation (2-3 days later). The second measurement was made after two months, the third one after one year (January 2015), the fourth one after 16 months and the last one after 26 months (March 2016). All the samples were collected during the normal operating cycle of the milling plant. Each intervention took three days, with two daily sampling moments, one in the morning and one in the afternoon.

2.1. KPI1: Debranning Ratio

As mentioned, KPI1 reflects the ratio between the flow-rate of the processed wheat and the flow-rate of the separated bran. To compute this indicator, we collected a series of 5 samples per sampling moment. Samples were collected by taking the bran output from the machines for

1 minute. Then, the bran was weighed and compared to the global productivity of the machine to derive the Debranning Ratio. The measurements were carried out both on the machine with the traditional wheels and on the machine with diamond wheels, at three different levels of energy absorption. At a constant flow rate, energy absorption can be assumed to be proportional to the residence time of the wheat into the debranner. Thus, during the three days of test, a total of 90 samples were collected on both the debranning lines, 30 for each energy absorption rate. This made it possible to derive statistically significant results.

2.2. KPI2: Wear Index of the wheels

The second KPI is a measure of the surface wear. It was calculated only for the innovative grindstone package with diamond wheels, in line with the fact that the analysis aims at developing a life-cycle model of this new device (while the behaviour of traditional wheels is already known and documented). As mentioned, the new grindstone package was equipped with 2 diamond wheels. In our analysis, we focused on the lower one, which is expected to be more subject to stress.

The Wear Index was calculated *via* image analysis. We took a series of pictures of the surface of the diamond wheels and analysed these by an image analysis software. The software has been specifically developed for this project from the working team of the University of Parma. We used a Dino-Lite Digital Microscope (model AD7013MT) to take the pictures, with a 50x zoom. Also in this case, data acquisitions were performed twice a day during the measurement campaign, each time taking about 100 photos on different (random) areas of the diamond wheel. An example of these pictures is proposed in Figure 3.

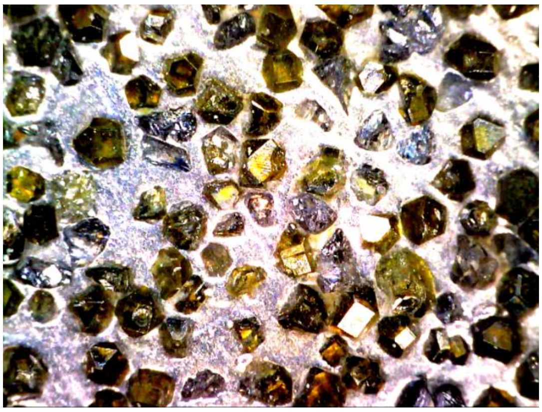

Figure 3 - Picture of the diamond wheel surface taken with digital microscope.

The software adopted is able to scan the colours of the pictures and to distinguish the diamonds from the metal surface. Therefore, it allowed to find out the size distribution of the diamonds at various time steps, as well as the diamond coverage of the wheels surface.

The KPI2 was then determined taking in consideration the average percentage amount of wheels surface covered with diamonds.

3. RESULTS AND DISCUSSION

3.1. Debranning yield over time

Figure 4 shows results for the Debranning Ratio. In this figure, the curves reflect the different power absorption levels, with both the traditional and diamond wheels. To be more precise, the red curves depict the performance of the silicon carbide wheels, while the blue ones those of the diamond wheels.

Typically, the useful life of traditional silicon carbide grinding wheels is indicated by the supplier and can be estimated in approximately 12 months, with some variations that may depend on the work load. In our experimental campaign, the traditional wheels needed to be replaced after about 14 months from the installation due to excessive wear, which led to the formation of deep cracks. This is why the relative curves span from 0 to 14 months.

Conversely, diamond wheels were still functioning after 26 months, and were replaced after 28 months (May 2016).

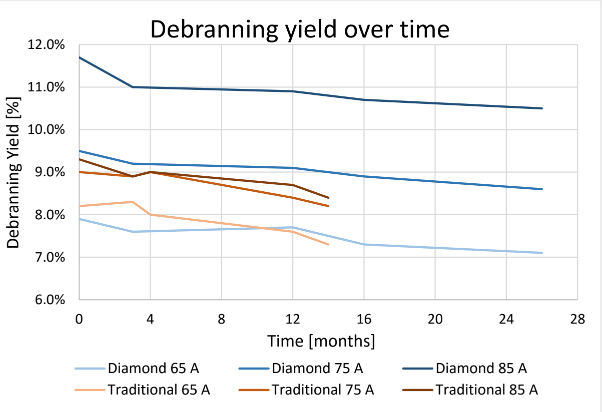

Figure 4 - Debranning ratio at different power absorption levels of the machine with traditional and diamond wheels.

Analyzing the results, it is easy to see that, no matter the device used, the debranning effectiveness immediately starts decreasing, with an almost constant rate during all life-cycle. During their life-cycle, both the silicon carbide and the diamond wheels suffered from a relative decline in the debranning yield of about 10%, reflecting the limit below which the wheat is likely to not be treated sufficiently. At this stage, the wheels need to be replaced. Figure 4 highlights some additional key points:

- At the lowest power absorption level the curves are all quite close. The traditional grindstone package has a higher initial Debranning Ratio, which however falls faster than the one of diamond wheels;
- The curves at 75 A absorption are slightly more distant, with diamond wheels showing a better performance. Also in this case the traditional package curve decrease more rapidly;

- At the highest power absorption rate, the distance between the two performances is instead very high. The diamond grinders index increase proportionally to the increase in power, while traditional wheels seem to reach a maximum effectiveness that could no longer be improved. This is probably due to the higher surface roughness of diamond wheels.

As previously mentioned, the general worsening of the performance in time is due to the surface deterioration of the wheels. Traditional grinding wheels wear out in an evident manner, with mineral material losses and changing of the wheel profile. The wear of diamond wheel is less noticeable, as there are no macroscopic damages, but nonetheless it causes loss of abrasiveness of the devices. KPI2 aims to quantify this latter point.

3.2. Diamond coverage over time

The second KPI was calculated *via* image analysis, and took into account the percentage amount of wheels surface covered with diamonds. Obviously, such a percentage will decrease in time, as a result of the progressive wear and detachment of diamonds. The decline of debranning yield can be right attributed to this phenomenon.

Experimental tests allowed us to derive the empirical curve shown in Figure 5**Errore. L'origine riferimento non è stata trovata.** that represents the wear of diamond wheels over time. The five measurement points are highlighted in the figure. Starting from these data, a mathematical law was extrapolated.

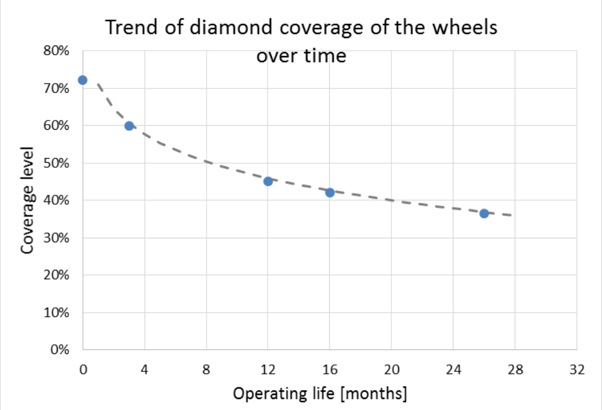

Figure 5 - Wear curve of the diamond wheels, representing the percentage of the wheel surface covered with diamonds over time.

The trend of the diamond coverage percentage in time follows an exponential law. On new wheels diamonds cover near 72% of the surface. In the first months of usage, the index reduction is higher: after 4 months the coverage level reaches 57%. Afterwards, the curve flattens progressively and after 12 months the reduction trend is almost linear. At the end of the useful life the index dropped to 36%. This means that the coverage has more than halved during the life of the grindstone package.

It emerged that the diamond coverage reduction can be caused by three main factors, i.e.:

- diamonds detachment from the metal layer;
- diamonds size reduction due to progressive erosion;
- diamonds breakage due to the frequent impacts.

3.3. Life-cycle model for the diamond debranning wheels

On the basis of the two KPIs computed, we were able to develop a life-cycle model of the diamond wheels. Such a model correlates the normalized debranning yield and the diamond coverage indicator.

To get comparable values for the various power absorption levels, the Debranning Ratio was normalized with respect to the maximum obtainable yield at a given power absorption level, which of course is always reached at the beginning of the life of the grinding wheels. Therefore, the debranning effectiveness of a grindstone package is always maximum (100%) with new wheels and decreases progressively.

After that, by means of a fitting procedure, we derived a mathematical model that correlates the normalized Debranning Ratio and the Wear Index. It is the life-cycle model of a grindstone package with diamond wheels, and represents the evolution of its operating performances with respect to its deterioration (see Figure 6). Such a model is not directly dependent on the time, meaning that it allows knowing the operating point of a grinding wheel simply by evaluating the wear, or even to predict the level of wear of a grinding wheel from the analysis of its debranning yield.

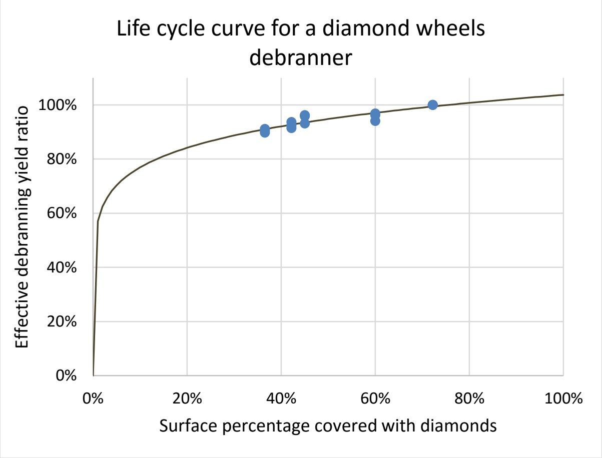

Figure 6 - Correlation between debranning yield and diamond residual coverage.

The graph in Figure 7 represents a detail of the life-cycle curve, at the higher level of Debranning Ratio. The red dotted lines represent the normalized yield limits: 100% is the new wheels condition while 90% is the limit acceptable effectiveness to have a compliant process. All the blue points are the various combination of yield and wear registered during the measurement campaign at every energy absorption level of the machine. The continuous line represents the life-cycle model of the diamond wheels.

The mathematical equation chosen to represent the relationships between the two KPIs is a power law, shown below:

$$f(x) = ax^k \quad (1)$$

Where: $a = 1.037$
$k = 0.130$

This equation shows a good fit with the sampling data ($R^2 = 0.834$), so the model seems to describe the samples with a good level of approximation.

When the coverage percentage reaches 0, the wheels have no action on the kernels. Then, it quickly rises up and it reaches an almost asymptotic trend at high levels of coverage.

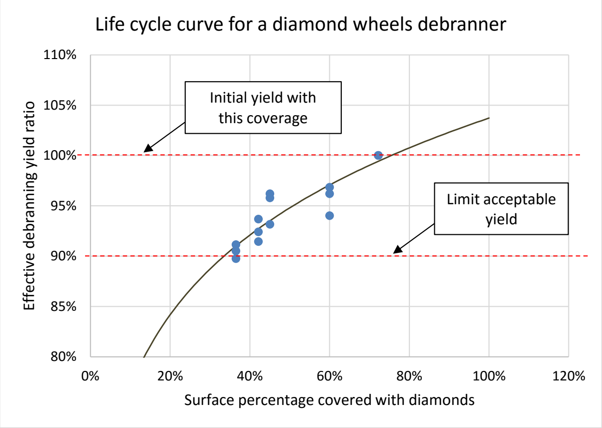

Figure 7 - Correlation between debranning yield and diamond residual coverage (detail of the curve).

With a coverage level higher than the one of the new wheels (72%), the model assumes a higher debranning yield, above 100%. However, the yield increase is modest, meaning that the abrasiveness of the devices does not significantly increase over the current coverage level. If reaching an ideal 100% coverage, the maximum yield would be only 3.7% greater than the current one.

4. CONCLUSIONS

The aim of the present work was to develop a life-cycle model for an innovative diamond grindstone wheels for wheat debranning. On the basis of the data collected through an extensive experimental campaign, we derived a mathematical model able to correctly describe the deterioration suffered by the grinding wheels during their useful life. The model allowed to obtain some important technical and economic conclusions on the diamond wheels compared to the traditional ones.

Traditional silicon carbide wheels, as previously mentioned, have an average useful life of about 1 year, which can vary as a function of the processed product. Moreover, their time to fail has a very relevant variability.

Innovative diamond wheels, instead, have a useful life of 26 to 30 months, with a much more controllable wear process, resulting in higher reliability. The data collected show a slower decrease of the debranning yield over time using diamond wheels compared to the traditional ones.

The developed model shows good accuracy in predicting the relationship between the two fundamental parameters that characterize the debranning process. By means of a simple analysis of the diamond wheel surface, the model allows to understand at what point in its life cycle it is, and what level of yield would be expected.

Future developments of this work might include the economic analysis of the two different solutions: as the investment required to build the innovative wheels is higher, it is essential to determine a payback point for this technology. Such a payback would be useful to identify the minimum duration of the diamond wheels that makes them preferable to the traditional ones from an economic point of view.

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