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Determination of the Relative Position Between Grinding Wheel and a Cylindrical Workpiece on a 7 Axis Grinding Machine by Acoustic Emission

The contact between grinding wheel and workpiece in the grinding process is recognized by acoustic emission (AE). Two acoustic emission monitoring systems (MS) were integrated into a 3 axis CNC grinding machine. A laptop allows the signal acquisition and visualization. The acquired AE_{RMS} signals from the contact between tool and workpiece are analyzed permitting to establish the most suitable AE monitoring system to recognize the contact in a particular grinding machine. In a second experimental setup the selected MS was installed on a 7 axis tool grinding machine at an industrial partner. At this partner, the relative position between grinding wheel and workpiece was previously determined manually. This procedure has a direct influence on the results depending on the technical skills of the operator. The automation of this activity supported by acoustic emission has led to satisfactory results regarding the relative position between grinding wheel and workpiece and contributed to the setup time reduction.

Keywords: monitoring systems, acoustic emission, external cylindrical grinding process

Introduction

In the manufacturing industry, the grinding process is one of the most common processes required when great quality and close tolerances are desired. A frequent way to improve such needs consists in using monitoring systems (MS) based on the acoustic emission (AE). Besides the possibility to control the process characteristics, these systems also allow an accurate detection of the contact between grinding wheel and workpiece. The position associated with the contact usually represents a reference, serving as a starting point to the following grinding operations.

In the first stage of the present work, the contact recognition between grinding wheel and workpiece is evaluated by two AE MS integrated into the CNC of the machine tool. Each MS works separately with specific AE transducers. The observation of the AE_{RMS} signals is done in real time on the screen of a laptop. The acquired contact signals are recorded and sampled aiming at additional analysis. The contact between grinding wheel and workpiece generates a grinding mark on the workpiece's surface. After the contact experiments the depths of the marks were measured in order to use these values as input data in a Factorial Analysis. The Factorial Analysis leads to the determination of an optimized condition to the contact recognition with minimal metal removal.

In a second stage the most suitable MS was installed in a tool grinding machine at an automotive part deliverer. During the machine setup, an activity that demands considerably amount of time consists in determining the reference position of the grinding wheel in relation to the workpiece. Due to the design characteristics of the machine tool and the lack of instrumented support, the machine operator needs to use try-error manual procedures. These procedures often result in errors and exert a direct influence on the machined geometry and do not permit to achieve the tied required tolerances. The present work suggests an instrumented procedure, based on AE, to automatically find the reference position between grinding wheel and workpiece.

Nomenclature

AE	= acoustic emission
$MS-A$	= monitoring system A
$MS-B$	= monitoring system B
$ZEROY_{AUTO}$	= procedure to automatically centralize the grinding wheel in relation to the workpiece's axis, using an AE monitoring system
a_e	= increment on the workpiece surface (infeed direction), mm
$a_{e,m}$	= depth of the measured mark, μm
$a_{e,SIGNAL}$	= depth of the mark evaluated by analyzing the AE_{RMS} signal, μm
t_A	= approaching time in the AE_{RMS} signal, ms
t_R	= rising time in the AE_{RMS} signal, ms
v_{fr}	= infeed velocity (radial direction), mm/min
v_s	= cutting speed, m/s
v_w	= workpiece speed, m/s
D_{MIN}	= inner diameter of the grooved profile, mm
$D_{MÁX}$	= external diameter of the grooved profile, mm
Y_A	= mean value of the measured marks obtained with MS-A, μm
Y_B	= mean value of the measured marks obtained with MS-B, μm
α	= significance level during statistical analysis (0.05)
ν	= degrees of freedom during statistical analysis
λ	= relative angular position between grinding wheel and the axis of the workpiece, degrees

Acoustic Emission on Grinding

Acoustic emission (AE) is defined as the transient elastic wave generated by the rapid release of energy from a localized source or sources within a material when subjected to a state of stress. This energy release is associated with the abrupt redistribution of internal stresses, and as a result, a stress wave is propagated through the material (Ravindra et al., 1997).

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The grinding process is characterized by the random contact of a large amount of cutting edges on the surface of the workpiece. All the individual contacts caused by the grits can be considered as a source of pulse deformation or stress on the workpiece. Figure 1 exemplifies the major AE sources that can be found in the grinding process (Karpuschewski, 2001).

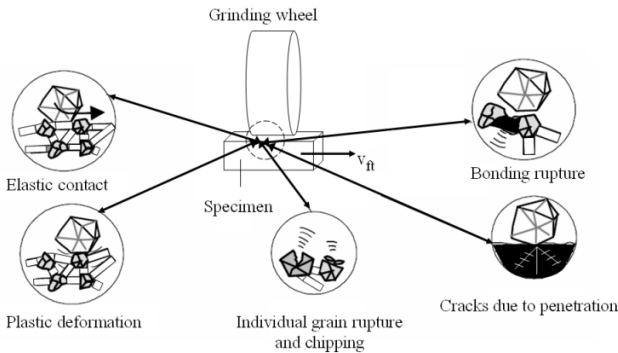


Figure 1. Sources of AE on grinding (Karpuschewski, 2001).

Acoustic emission signals on grinding

The raw AE signal (AE_{RAW}) is composed of different high frequencies on different energy levels and is difficult to interpret. One of the most employed techniques to extract useful information from AE_{RAW} signals consists in using the root mean square value (RMS) of the AE_{RAW} signals (Hwang et al., 2000). The AE_{RMS} represents a physical dimension of the AE_{RAW} signal intensity and depends directly from the amount and dispersion of stress waves on the material (Meyen, 1991). According to Hwang et al. (2000), the AE_{RMS} signal is defined as:

$$AE_{RMS} = \left[\frac{1}{\Delta T} \int_0^{\Delta T} v^2(t) dt \right]^{1/2} \quad (1)$$

where:

V = raw acoustic emission signal (AE_{RAW}), and
 ΔT = integration time constant.

The AE_{RMS} (rectified value of AE_{RAW} signal) has been successfully used to monitor several grinding situations. However, the spectrum analysis can complement the interpretation in situations where the RMS technique cannot allow satisfactory results (Gomes, 2001).

Acoustic emission signals during the contact between grinding wheel and workpiece

The contact recognition between grinding wheel and the workpiece depends on the transducer, the amplifier and the signal conditioning. This leads to a time delay and the first physical contact of grits and workpiece may happen before any appreciable change in the signal, especially when employing AE_{RMS} signals. The contact is usually judged according to a significant change of the amplitude of the AE_{RMS} signal, or AE_{RAW} signal. Therefore, understanding the instantaneous features regarding wheel/workpiece interaction may help to define “contact” for performing efficient use of the AE_{RMS} signal (Dornfeld et al., 1995; Leme, 1999; Dornfeld and Oliveira, 2001). Theoretically, the cutting grit generates a burst type of AE signal when it cuts through the workpiece. When numerous grits cut through the workpiece in such a way the interval of two consecutive cuts (which are not necessarily in the same

place) is much shorter than the decay time of each burst signal, then a continuous type of AE signal is formed (Webster et al., 1996). The continuous AE signals generated when many grains randomly touch the surface of the workpiece can be represented by diverse parameters, Fig. 2 (Asher, 1997).

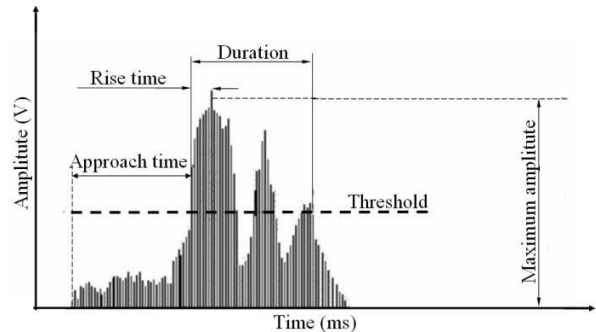


Figure 2. Characteristics parameters on AE signals (Asher, 1997; Ravindra et al., 1997).

Experimental Setup for Contact Recognition Experiments

The experimental setup used for the contact recognition experiments performed in a cylindrical CNC grinding machine (Zselics Pratika Flexa 600-L) is schematically represented in Fig. 3.

Two AE monitoring systems were used separately. The AE signals related to the event of contact were recognized by employing piezoelectric AE transducers with direct transmission. The AE_{RAW} signals from the transducers are transmitted to the MS through appropriate cables. When MS-A (Dittel, 2007) was used, the AE_{RMS} signals were sent directly to a laptop by a RS-232 interface and visualized on the laptop’s screen after treated by a specific software (Dittel, 2007). When MS-B was used (Sensis, 2002), the AE_{RMS} signals assigned to its analog output were sent to a multi-analyzer system (Oros, 2006) and to a laptop and the results are presented on the screen. All data were stored for a further analysis.

Both MS carry out the signals treatment in order to convert the AE_{RAW} signal into AE_{RMS} signal. The signal conditioning chain for the MS-A includes many stages: amplification, band-pass filtering, rectifying, and low-pass filtering at the end. MS-A uses a specific software to digitalize the AE_{RAW} signal up to 1000 Samples/s, based on the highest cut-off frequency in the conditioning chain, and then avoiding aliasing errors. MS-B has a similar signal conditioning chain permitting to sample the AE_{RAW} signals at 2048 Samples/s with the aid of a particular analyzer (Oros, 2006), and then, avoiding aliasing errors.

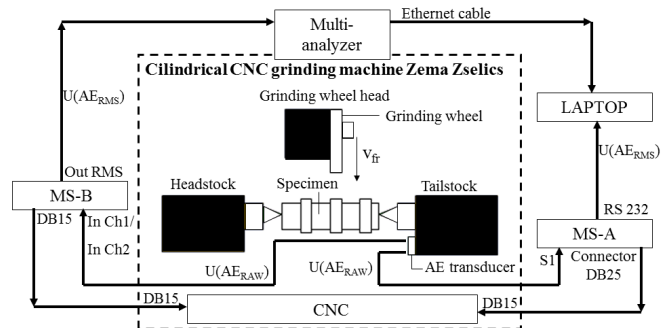


Figure 3. Experimental setup for contact recognition (Boaron, 2009).

Both MS were connected to the CNC of the grinding machine by means of a DB-15 connector installed into the CNC of the machine. As the AE_{RMS} signal from the contact exceeds a static threshold (previously adjusted by the user), a electric signal is delivered to a specific input in the CNC, which acts on the stoppage and reverses the grinding wheel's infeed motion (Boaron, 2009).

Experimental Procedure for Contact Recognition Experiments

The experiments were carried out in plunge grinding of ABNT 1040 steel specimens with a CBN grinding wheel (406 mm diameter). During the contact recognition experiments the specimen was kept static ($v_w = 0$ m/s) without cutting fluid. The cutting speed of the grinding wheel was maintained constant at $v_s = 22.5$ m/s.

Before starting the experiments, the grinding wheel was dressed, the AE transducers installed, and both MS were adjusted. The adjustments of the MS were firstly realized by setting the available filters in order to avoid the background noise influence in the AE contact recognition signals. The parameters related to the static threshold, gain, and RMS time constant play an important role in the contact recognition procedure. The parameters selection has been based on the binary technique (Dornfeld and Oliveira, 2001), i.e., threshold and RMS time constant should be as small as possible, and gain and noise reduction parameters, as high as possible.

Due to the fact that the amount of material removed on each contact experiment is very small and the specific removal rate Q_w is also very small, the wear of the CBN grinding wheel can be disconsidered. The specimen was fixed between the tailstock and the headstock and positioned orthogonally to the infeed direction, as illustrated in Fig. 4(a).

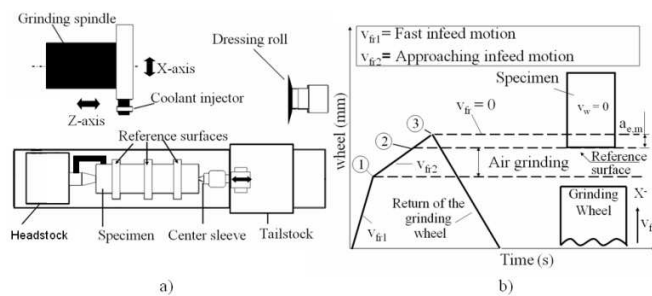


Figure 4. a) Working chamber of the grinding machine. b) Infeed motions of the grinding wheel.

At the beginning of each experiment the grinding wheel is positioned 250 mm from the specimen ($X^+ = 250$). Figure 4(b) shows the stages of movement described by the grinding wheel during the experiments. The grinding wheel plunges with the infeed velocity $v_{fr1} = 600$ mm/min to a position at 0.5 mm away from the specimen (point 1 in Fig. 4(b)). Thereafter, the infeed velocity is dropped to the infeed velocity v_{fr2} , until the contact is recognized by the AE monitoring system (point 2 in Fig. 4(b)). At this point the infeed motion is automatically stopped and reversed by the CNC of the grinding machine. The relative displacement described by the grinding wheel from point 2 to point 3 defines the depth of the mark a_c on the surface of the specimen. This depth is due to the time delay in processing the signals and informing the CNC, as well as the time delay of the CNC to stop and reverse the infeed movement of the grinding wheel.

The contact between grinding wheel and the specimen is featured by a physical mark on the specimen's surface, which results from the material removal from the specimen during the time between the first contact of a grit and the workpiece until the

complete stoppage of the infeed motion and relaxation of all elastic deformations of the system after the reversion of the infeed motion. The level of the AE signals depends on factors like the infeed velocity of the grinding wheel v_{fr} , the integration time constant ΔT , the transducers (magnetic or threaded fixture) and the AE monitoring system. These factors have been varied to produce contact recognition marks on the specimen. The two AE monitoring systems have been used separately.

Structure of the Contact Recognition Experiments

The experiments were conducted based on a Factorial Analysis involving the 3 major factors which influence on the first contact AE_{RMS} signals. Among these factors were considered the infeed velocity v_{fr2} , the integration time constant ΔT , and the type of the employed transducers in the experiments. These 3 factors were varied in 2 levels (high \uparrow , and low \downarrow) whose magnitudes were previously defined, Table 1.

Line 1A illustrates the experimental situation in which the factors "Integration time constant" (ΔT), "transducer", and "infeed" are set at the lower levels (10 ms, magnetic sensor, 3 mm/min, respectively). On the used abbreviation, the number 1 means the first combination between factors and levels, whereas letter "A" means the MS-A was used (instead of MS-B). Each experimental situation was repeated 6 times, leading to a total of 48 experiments for each MS. When using the MS-B the same methodology was implemented. The only difference consisted in the higher value (\uparrow) for the factor "Integration time constant" (ΔT), which assumed the value 400 ms.

Table 1. Combinations of the factors and their respective levels of variation.

MS-A			
Experiments (Abbreviation)	Integration Time Constant (ms) $\uparrow = 333,33$ ms $\downarrow = 10$ ms	Transducer $\uparrow =$ threaded base $\downarrow =$ magnetic base	Infeed (mm/min) $\uparrow = 6$ mm/min $\downarrow = 3$ mm/min
1A	\downarrow	\downarrow	\downarrow
2A	\downarrow	\downarrow	\uparrow
3A	\downarrow	\downarrow	\downarrow
4A	\uparrow	\downarrow	\downarrow
5A	\downarrow	\uparrow	\downarrow
6A	\downarrow	\uparrow	\uparrow
7A	\uparrow	\uparrow	\uparrow
8A	\uparrow	\uparrow	\downarrow

The depths of the marks generated during the contact, measured in a precision metrology device (Mahr MMQ40 Formtester), were used as input data on a Factorial Analysis which permitted an optimized use of both AE monitoring systems in recognizing the first contact and to verify the effectiveness of the AE monitoring systems.

Contact Recognition Results

Through the realization of the Factorial Analysis, an optimizing condition for the contact recognition was achieved for each MS. This condition takes into account all the combinations between the 3 factors involved and their respective levels of variation. The input values for this analysis were the values of the depths of the measured marks ($a_{e,m}$). The optimized condition has been characterized by the specific combination of factors and levels that present the mark with the smallest value of depth. Figure 5 shows the analyzed results for MS-A and MS-B. Y_A means the average value of the depths of the marks when using MS-A, whereas Y_B is

the average value of the depths of the marks when using MS-B. For both MS the optimized condition is represented by a small v_{fr2} , the transducer with the magnetic base, and low integration time. The constant values that appear at the beginning of both equations represent the mean values of $a_{e,m}$ along the 48 runs for each MS. Additionally, the coefficients refer to the statistical effect of the analyzed factors on the mean values of $a_{e,m}$.

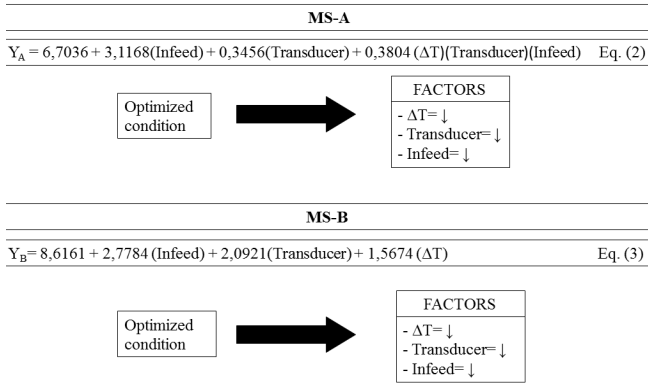


Figure 5. Optimized results for the contact recognition.

Based on these results, the values of the infeed velocity v_{fr2} were gradually reduced for each MS in order to carry out a comparative study regarding the efficiency in recognizing the first contact. The contact signals were recorded and post-analyzed and showed to decrease when reducing the infeed velocities, as it is known from the literature (König et al., 1994; Dornfeld et al., 1995; Klocke, 2009). The obtained marks in this experiment were also measured by the same way as done before, Table 2.

Table 2. Depth of the marks obtained with the infeed velocity variations.

		$a_{e,m}$ related to different values of v_{fr2}									
v_{fr2} (mm/min)		1.5	1.5	1.0	1.0	0.5	0.5	0.3	0.3	0.1	0.1
MS		B	A	B	A	B	A	B	A	B	A
$a_{e,m}$ (mm)		0.83	1.77	0.52	1.31	0.22	0.44	0.13	0.22	0.13	0.09

Despite the lower values observed in the majority of the situations when using MS-B (except for $v_{fr2} = 0.1$ mm/min), it was not possible to affirm that this system would have a better efficiency than MS-A only by a simple comparison of these values. Therefore, an additional study was realized to compare both MS. This study was based on a Statistical Hypothesis Testing which considered the difference in the means of the obtained depths by using the optimized situation determined earlier (See Eq. (3) and Eq. (4)). This experiment starts with two initial hypotheses (H0 and H1). The hypothesis H0 considers that the difference in the means is zero, (that is, $H_0: \mu_A - \mu_B = 0$) and the hypothesis H1 considers that the difference in means verified during the experiments should represent a better efficiency by the MS-B (that is, $H_1: \mu_A - \mu_B > 0$) conducting to small values of the marks on the specimen after the contact recognition. During the evaluations, a significance level of $\alpha = 0.05$ was used. Figure 6 shows the major statistical parameters which have been determined to achieve the conclusion about the available efficiency for both MS.

According to Montgomery (2001), as $T_0 > t_{0,05;12}$ then the hypothesis H0 ($H_0: \mu_A - \mu_B = 0$) must be rejected and the hypothesis H1 can be accepted. Based on these results, it is possible to conclude that the observed difference on the mean values (\bar{x}_A and \bar{x}_B) is representative in terms of a statistical sense. Then it can be affirmed that the MS-B has presented a better efficiency in recognizing the first contact when using the optimized condition predicted by the model.

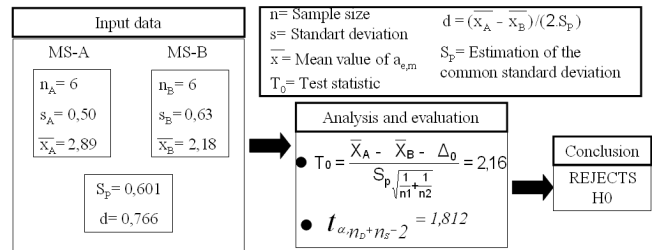


Figure 6. Statistical parameters used while evaluating the Hypothesis Test.

Analysis of the AE_{RMS} Signals from the Event of Contact

After determining the optimized conditions for both MS the experiments were conducted in order to predict the depths of the marks by employing the AE_{RMS} signal as a reference. For each MS, six repetitions were executed and their AE_{RMS} signals have been recorded. The contact recognition signals were described and analyzed based on the parameters shown previously (see Fig. 2). By assuming that: a) the stoppage of the grinding wheel motion is associated with the higher value of the AE_{RMS} signal; b) during the time characterized by the parameter t_A (approaching time) the infeed velocity v_{fr2} is equal to the programmed velocity; c) the infeed velocity v_{fr2} is uniformly decelerated during the time represented by the parameter t_R , which is associated to the first overstepping of the static threshold; d) the displacement of the grinding wheel along the decelerated movement numerically corresponds to the area in the graphic $v_{fr2} \times t$ (uniformly decelerated motion). Regarding the AE_{RMS} signals connected to the experiment 1A1, the evaluation of the depth of the mark corresponds to the time in which the AE_{RMS} signal is recognized. The depth of the mark was evaluated by the following manner:

Approaching time, t_A : $t_{A,1A1} = 4$ ms
 Rising time, t_R : $t_{R,1A1} = 228$ ms
 Infeed velocity, v_{fr2} : $v_{fr2} = 3$ mm/min = $50 \mu\text{m/s}$

$$a_{e,SIGNAL} = t_A \times v_{fr2} + (t_R \times v_{fr2}) / 2 \tag{4}$$

then

$$(a_{e,SIGNAL})_{1A1} = 5.95 \mu\text{m}$$

The same procedure has been used to the evaluations involving the other signals (1A2 to 1A6 and 1B1 to 1B6). Figure 7 displays the depth of the marks obtained after measuring ($a_{e,m}$) as well as the depths evaluated through the analysis of the AE_{RMS} signal, ($a_{e,SIGNAL}$). Observing the obtained values it is possible to conclude that the values related to $a_{e,SIGNAL}$ were considerably higher than those obtained by $a_{e,m}$, for every experimental conditions for both MS. This information makes sense as the AE contact signal in this process happens much earlier than any notable material removal. At the beginning of the contact, the elastic strains related to the system (grinding wheel, workpiece, machine tool) increased until plastic

strains initiate to dominate. The initial plastic strains are not enough to cause any material removal. As the plastic strain reaches a specific level, the removal process begins to occur, being characterized by chip formation. After the infeed stoppage, the contact between grinding wheel and workpiece still occurs until the moment in which every elastic strains are attenuated (König, 1989; Dornfeld and Lee, 2008; Klocke, 2009; Boaron, 2009).

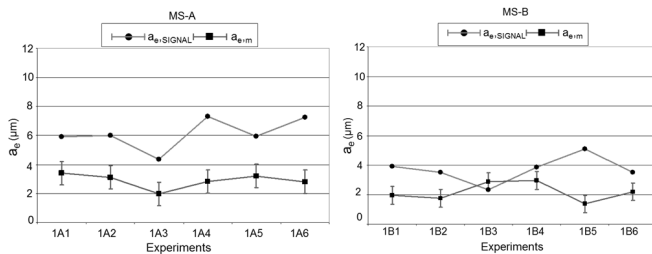


Figure 7. Obtained values of $a_{e,m}$ and $a_{e,SIGNAL}$.

Experimental Setup for the Relative Position Experiments

Despite the better contact recognition accuracy presented by MS-B (Fig. 7), the MS-A was used in an industrial application due to its flexibility and easy-to-use characteristics. In addition, cost factors have also been decisive as MS-B needs an auxiliary analyzer in order to digitalize the AE_{RAW} signals and to allow a signal analysis. The designed setup for experiments was implemented in a cylindrical CNC tool grinding machine for broaches (Stauffer/Zen), Fig. 8.

The axis x , y , z and a (rotation of the workpiece) are CNC controlled. The rotation of the grinding wheel (b) and the additional rotational axis $b1$ and c (rotation and tilting of the wheelhead) are manually operated with indication of the angular position on the CNC's screen. The grinding speed and feed rates are controlled by the CNC program. The grinding wheel has a diameter of 100 mm. The maximal workpiece length is about 1000 mm. As a manner to allow the implementation of the automatic contact recognition between grinding wheel and workpiece, the MS-A is integrated into the CNC.

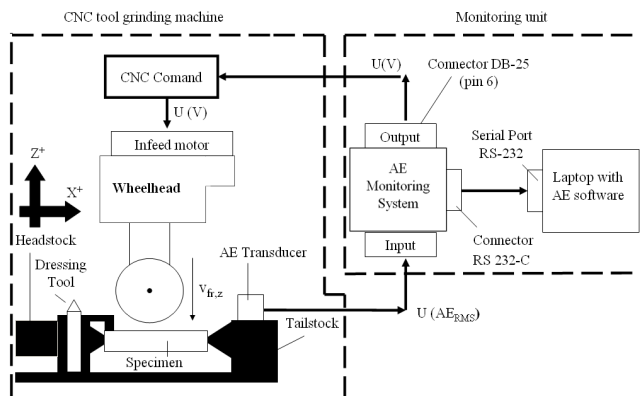


Figure 8. Experimental set up for the tests in industry (Boaron, 2009).

The AE transducer was screwed on the tailstock. This position showed the lowest interference from the moving components on the machine and a good signal from the process. The outputs from MS-A were delivered to the CNC by means of pin-6 (connector DB-25) of the MS-A. This pin is associated with the digital output from the MS-A and delivers a voltage signal to the CNC input every time the

AE_{RMS} signals (from the contact) exceed the static threshold previously adjusted by the user. The AE_{RMS} signals were directly sent to a laptop with a specific MS-A software through a RS-232 interface and could be visualized on the laptop's screen. This software digitalizes the AE_{RAW} signal using a sampling rate up to 1000 Samples/s avoiding aliasing problems. In parallel, the coordinates associated with the spark in and spark out signals are stored in the CNC.

Experimental Procedure to Determine the Relative Position

The main goal of the experiments consisted in implementing a procedure to automatically determine the centralized cross position of the grinding wheel in relation to the specimen. All the experiments have been executed without cutting fluid. The centralized cross position between grinding wheel and specimen is associated with the Y-axis of the grinding machine so that the procedure receives the name $ZEROY_{AUTO}$. The term "ZERO" refers to the centralized position, whereas the term "AUTO" means the automatic use of the AE_{RMS} signals from the spark in and spark out events. During the experiments to verify the $ZEROY_{AUTO}$ procedure the specimen was kept static ($v_w = 0$ m/s). The contact between grinding wheel and the specimen behaves as described before. It is always desirable to achieve the smallest mark as possible to minimize the influence on the dimensional tolerances of the workpiece.

Even considering that the metal removal during the centering experiments is extremely small, before starting each group of experiments to verify the $ZEROY_{AUTO}$ procedure, the grinding wheel was dressed with a symmetric profile and the MS-A parameters were adjusted based on the binary technique (Oliveira and Dornfeld, 2001). At the beginning of each experiment the grinding wheel was positioned in a secure distance above the surface of the specimen ($Z+ = 2$ mm), close to the centralized position of the grinding wheel in respect to the specimen's axis, (Fig. 9, position "b" at left). The grinding wheel is then ordered to move toward the workpiece ($v_{fz} = 10$ mm/min) on the Z-axis until the contact with the specimen is recognized by the MS-A and the infeed motion is stopped (Fig. 9, position "a" at left). The recognized contact position is stored in the CNC for further use. The grinding wheel returns to the safe position "b" and moves along the Y-axis for about 10 mm and more 10 mm on the X-axis (Fig. 9, position "c" and "d" respectively). The grinding wheel is ordered to move in Z-axis down to the "z" coordinate and incremented 0.01 mm (a_{e1}) in relation to the reference position recognized earlier on point "b", then reaching point "e". The grinding wheel moves along the Y-axis crossing the workpiece completely until point "f". During this trajectory the grinding wheel touches the workpiece. This contact is recognized by the MS-A and is represented by the smaller mark on the specimen's surface. The AE signals in this first interaction have shown to be not adequate for a centering procedure. The position of the grinding wheel is incremented for up to 0.01 mm (a_{e2}) along the Z-axis, position "g", and then returned to the position "h" on the back side of the specimen. During this movement the coordinates associated with the spark in (Y1) and the spark out (Y2) positions are stored into the CNC and serve as reference positions for centering the grinding wheel in respect to the specimen. The grinding wheel is lifted to position "i", moved to "j" and "k" centered over the workpiece axis and plunged into the specimen until the contact is recognized, Fig. 9 (position "l"). The coordinates of this contact position are also stored (Boaron, 2009).

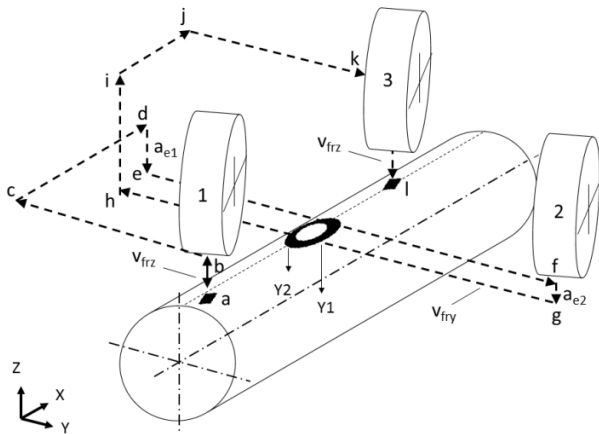


Figure 9. ZEROY_{AUTO} sequential movement.

Structure of the Relative Position Experiments

The structure of the experiments is divided into two stages (stage-a and stage-b). The stage-a experiments aimed to determine the appropriate conditions in recognizing automatically the centralized position between grinding wheel and specimen by analyzing the major influencing factors on the AE_{RMS} signals and thence on ZEROY_{AUTO} procedure. During this stage, the values of the centralized position by using the ZEROY_{AUTO} procedure were compared to the mean value achieved when using the manual procedure. Among the factors that significantly influence the ZEROY_{AUTO} procedure are the cutting speed v_s , the depth of cut a_{e2} , the traverse infeed along the Y-axis v_{fry} , and the value of the integration constant time ΔT (selected on the MS-A). Moreover, the relative angular position between grinding wheel and specimen λ has also shown an evident influence on the AE_{RMS} signals and, consequently, on the centering values by using the ZEROY_{AUTO} procedure. This angle was chosen equal to $\lambda = 18^\circ$ and $\lambda = -60^\circ$, representing the angular limits of the helical angles of the broaching tools to be manufactured. Figure 10 shows a schematic top view of the tool grinding machine's working chamber and the angular positions used during the experiments.

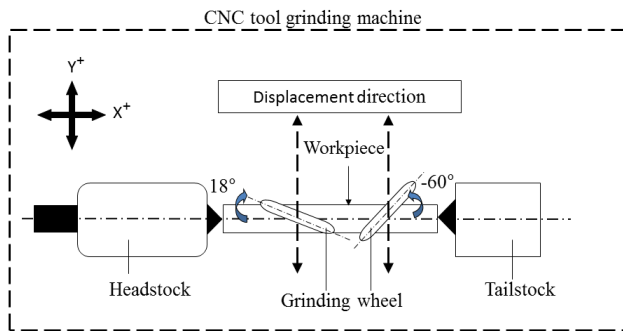


Figure 10. Schematic top view of the working chamber.

The 4 mentioned factors were varied each at 2 levels following the scope of a Factorial Analysis. The combination of the 4 factors and their respective levels of variation have led to a total of 16 experiments, Table 3.

For each of the 16 experiments, 3 repetitions (R1, R2, R3) have been done in order to achieve a representative mean value and a standard deviation of the centered position, using the ZEROY_{AUTO}

procedure. The mean value for each experiment was compared to the mean value of the manual procedure.

Table 3. Combination of factors and their respective levels of variation.

EXPERIMENTS	FACTORS				REPETITIONS			ZEROY _{Aero} (Mean)	ZEROY _{Aero} (Standart Deviation)
	Δt (ms)	v_{fry} (mm/min)	a_{e2} (mm)	v_s (m/s)	R1	R2	R3		
	$\uparrow=33,33$ $\downarrow=10$	$\uparrow=300$ $\downarrow=200$	$\uparrow=0,01$ $\downarrow=0,05$	$\uparrow=21,4$ $\downarrow=26,2$					
1	↓	↓	↓	↓	180,629	180,806	180,804	180,746	0,082
a	↓	↓	↓	↓	180,395	180,645	180,724	180,588	0,171
b	↓	↓	↓	↓	180,565	180,312	180,423	180,433	0,126
c	↓	↓	↓	↓	181,241	181,37	181,338	181,316	0,067
d	↓	↓	↓	↓	180,833	180,937	180,743	180,837	0,097
ab	↓	↓	↓	↓	180,226	180,245	180,245	180,238	0,010
ac	↓	↓	↓	↓	180,547	180,676	180,93	180,717	0,194
ad	↓	↓	↓	↓	180,607	180,19	180,659	180,485	0,257
bc	↓	↓	↓	↓	180,624	180,978	181,008	180,874	0,213
bd	↓	↓	↓	↓	180,659	180,358	180,451	180,489	0,154
cd	↓	↓	↓	↓	181,126	181,541	181,429	181,365	0,214
abc	↓	↓	↓	↓	180,543	180,092	180,143	180,259	0,246
abd	↓	↓	↓	↓	180,496	180,201	180,054	180,250	0,225
bcd	↓	↓	↓	↓	180,541	180,684	180,889	180,704	0,174
adc	↓	↓	↓	↓	180,694	181,303	181,482	181,159	0,413
abcd	↓	↓	↓	↓	180,209	180,215	180,139	180,187	0,042

The levels of variation have been determined by observing the boundary limits to be used without damaging the machine. These values also corresponded to those normally used during the real jobs on the machine. The level of variation connected to the factor ΔT was selected in such a way that the ZEROY_{AUTO} procedure could be implemented. The analysis of the 4 factors has been carried out for the critical angular positioning $\lambda = -60^\circ$. The results for this position were compared to the results for $\lambda = 18^\circ$. The best results obtained automatically were close to the mean value obtained manually. Table 3 detaches the combination of factors presenting the best achieved results. After conducting the 48 experiments regarding the stage-a experiments, it was possible to verify the experimental conditions which conducted to the nearest mean values between both procedures (ZEROY_{AUTO} and the manual procedure). Among all the 16 experimental conditions just 4 have shown to be useful. The best results were achieved when using the experimental conditions "ab", "abc", "abd", and "abcd" which are detached in Table 3. By employing the condition "ab" the angular position of the grinding wheel was then modified to $\lambda = 18^\circ$ and the ZEROY_{AUTO} procedure was verified again. Table 4 shows the obtained results after 6 repetitions using this condition:

Table 4. Achieved results when using the condition "ab" and the angular position $\lambda = 18^\circ$:

REPETITION	R1	R2	R3	R4	R5	R6	MEAN SAUTO	(mm)
ZEROY _{AUTO}	47.949	47.952	48.067	48.066	47.903	47.901	47.973	0.069
ZEROY _{MANUAL}								48.122

Despite the difference in about 0.15 mm observed in the mean value founded with ZEROY_{AUTO} procedure in comparison to the mean value obtained through the manual procedure (ZEROY_{MANUAL}), the results have shown this experimental condition could be considered as possible to be used on both angular positions of the grinding wheel ($\lambda = 18^\circ$ and $\lambda = -60^\circ$) leading to close values between both procedures. Meanwhile, to prove the real efficiency in finding the centralized position with ZEROY_{AUTO} procedure, it was necessary to analyze the results obtained along the second phase of the experiments, stage-b.

The stage-**b** experiments consisted in comparing the efficiency of the ZEROY_{AUTO} procedure and the manual procedure in achieving a centralized symmetric groove on a specimen for the angular position of $\lambda = 18^\circ$. The comparison was made by measuring the ground groove on the specimen. The groove was measured on a coordinate measuring machine and referenced to the axis of the workpiece and the reference profile. In this procedure the reference profile is independent of the judgment of the grinding machine operator. The machined groove profile was scanned and exported to specific software allowing the visualization of the actual and the designed profile. The software also permitted to determine the distances between the measured and designed profile on desired positions.

Results and Analysis for the Relative Position Experiments

Along the stage-**a** experiments, all the AE_{RMS} signals originated during the interaction between grinding wheel and workpiece could be recorded and analyzed. Figure 11 shows a representative AE_{RMS} signal captured along the second traverse movement of the grinding wheel in relation to the specimen (displacement $g \rightarrow h$).

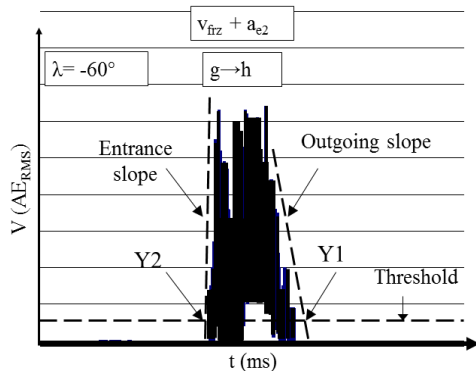


Figure 11. Characteristic of the AE_{RMS} signal during displacement $g \rightarrow h$.

It is possible to observe that the entrance slope is higher than the outgoing slope. This behavior is highlighted through the auxiliary dashed lines in the figure. The difference in the entrance and outgoing slopes is due to the metal removal at the beginning and at the end of the contact between the grinding wheel and the specimen. During the traverse movement of the grinding wheel in respect to the specimen, the metal removal starts when the first corner of the grinding wheel gets in contact with the specimen and stops when the second corner of the grinding wheel loses contact with the specimen. During the time the grinding wheel is in contact with the specimen a nearly continuous AE_{RMS} signal is generated.

The obtained results during the stage-**b** experiments have been achieved with an angular positioning of $\lambda = 18^\circ$ and a grinding wheel presenting a symmetric involute profile. For a first approach, the grinding wheel was manually centered. The 4 best experimental conditions that have been encountered previously were verified with ZEROY_{AUTO} procedure, in order to guarantee a reliable result. The combination “ab” (see Table 3) has led to the closest mean value to those obtained manually (54.84 with ZEROY_{AUTO} procedure, against 54.83 obtained with manual procedure). By using these mean values of the centralized position, a groove was machined on the specimen for each centralized position. Thereafter, the position of the grooved profile was measured in relation to the axis of the specimen. To compare the efficiency of both procedures in reaching a centralized position between grinding wheel and specimen, it was necessary to evaluate the deviations from the designed profile. Figure 12 illustrates an example of the measured profile (continuous lines) and the overlapping of the designed profile (dashed lines).

The scanned profile (measured profile) shows to be extremely out of the desired tolerances. As the main goal of this study was related to the determination of a centralized position between the grinding wheel and specimen, the correction of the dressed profile has to be done in a second step, out of the scope of this research. It is shown that the achieved centralization by using both procedures presents a good result in terms of the relative position to the designed profile. Both procedures lead to machined grooves whose profiles appear to be adequately centralized in reference to the designed profile.

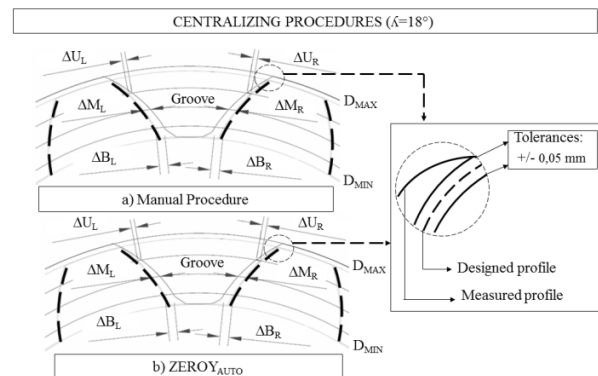


Figure 12. Achieved centralization by using the manual procedure and ZEROY_{AUTO} procedure.

The symbol Δ corresponds to the gap (error) between the measured and the designed profile. The letters “R” and “L” represent the sides of the groove in which the measurement of the deviations was carried out (“right” and “left” side, respectively).

Figure 13 compares the measured values at the upper (U), middle (M) and bottom (B) positions of the ground and designed profiles by using both centralizing procedures. The deviation of the centralized position is also shown. The software that superposes the measured and the designed profiles considers the best fit at the middle position M. If there is a deviation at the top, it indicates that the centralization of the grinding wheel is not adequate. The centralization that has been done by the operator (manual procedure) shows a deviation of 0.01 mm at the upper position, which is close to the required tolerances limits and far worse than that achieved by ZEROY_{AUTO} procedure.

CENTRALIZING PROCEDURES ($\lambda=18^\circ$)							
Manual Procedure				ZEROY _{AUTO}			
Measuring Position	Deviations			Measuring Position	Deviations		
	Δ_L (mm)	Δ_R (mm)	Δ (mm)		Δ_L (mm)	Δ_R (mm)	Δ (mm)
U	0,091	0,101	0,01	U	0,088	0,085	0,003
M	0,168	0,168	0	M	0,162	0,162	0
B	0,201	0,208	0,007	B	0,197	0,204	0,007

Figure 13. Achieved centralization by using the manual procedure and ZEROY_{AUTO} procedure.

Conclusions

Based on the results that have been presented, it was possible to verify that both AE monitoring systems are feasible to detect the first contact between grinding wheel and specimen. The obtained results from the Factorial Analysis show the average values of the marks when using the MS-A and MS-B were $x_A = 6.7 \mu\text{m}$ and

$x_B = 8.6 \mu\text{m}$, respectively (Eq. (2) and Eq. (3)). The final results achieved from the Statistical Hypothesis Testing have exhibited a better efficiency by MS-B in recognizing the contact on the 3 axis CNC grinding machine employed. This behavior was also verified when comparing the average values of the measured marks ($a_{e,m}$) and the averages values of the marks obtained by analyzing the AE_{RMS} signals ($a_{e,SIGNAL}$) from the contact events.

The proposed procedure (ZEROY_{AUTO}) is feasible to be implemented in a practical sense, especially when analyzing the angular position of $\lambda = 18^\circ$, which represents the smallest helical angle used for machining the broaching tools. As a first advantage, the ZEROY_{AUTO} procedure has led to an insignificant deviation in relation to the designed profile (0.003 mm at the top measuring section) while the use of the manual procedure conducted to a higher deviation (0.01 mm) at the same measuring section. The second advantage that was noted in using the ZEROY_{AUTO} procedure consists in the centering time of 30 s required to determine the centralized position between grinding wheel and the specimen. The production is habilitated to start after finding the centralized position. The manual procedure takes an average time of about 5 min to find a centralized position. For this procedure it was always necessary to control the position of the first ground groove in the metrology laboratory, demanding time (up to several hours) to start production.

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