EVALUATION OF MACHINED SURFACE ROUGHNESS THROUGH ACOUSTIC EMISSION

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Abstract. *Modern manufacturing technologies are continually tending towards automation of the production process due to an increasing demand for high production. In metal cutting operations, surface roughness monitoring as well as other parameters such as tool wear and cutting force are essential requirements in the drive towards automatic process. Acoustic Emission (AE) based sensing technique has becoming more popular because of its effectiveness, which allows understanding the behaviour of surface roughness and tool wear during the operation. The objective of this work is to investigate the relationship between acoustic emission signal (RMS) and surface roughness in turning operation of AISI 1045 carbon steel. The surface profile is obtained perpendicularly to the feed marks on the machined surface in a sample length of 4 mm. The AE signals are acquired during the operation every time the tool passes the region where the roughness will be measured, at a rate of 400 points per rotation of the workpiece. The cutting parameters were kept constant: cutting speed 120 m/min, feed rate 0.079 mm/rot and depth of cut 0.5 mm. It was used new cutting edges and also tools with some previous flank wear (VB_{Bmax}=0.31 mm) to obtain different roughness and also to verify the effect of tool wear in the acoustic emission signal. The results shown that while there is no relationship between AE signal and the Ra parameter, there is a very good relationship between AE and R_{sk} (skewness) or R_{ku} (kurtosis) for a new cutting edge. It was also observed that tool wear affects the signal and the correlation with surface roughness. The parameters R_{sk} and R_{ku} increase with AE signal for new cutting edges.*

Keywords*: Turning, Acoustic Emission, Surface Roughness.*

1. Introduction

Modern industries that use manufacturing processes direct their efforts towards reducing costs and improving productivity, in particular, industries that use machining processes. These are because machining processes are the most used process for manufacturing operations (Trent, 1984). With this objective, and also to improve products quality, researches have been developed in the direction to monitor cutting processes. A large variety of sensors and signal processing methods have been employed to monitor cutting force, temperature, tool wear and failure and the surface roughness. Vibration signals from the machine tool are measured to monitor surface roughness in turning operations with good correlation. Acoustic emission (AE) are used to monitor tool wear in conventional cutting operations. The great advantages of vibrations and AE sensors is no interference with the cutting operation.

The intention to correlate the AE with the generated profile of the workpiece can be an important and consistent tool for the industry on its competition for the market, each time more disputed and globalised. Moreover, equipment for AE signal acquisition is relatively cheap, and they are not complicated to operate and to understand.

According to Kakino (1980), AE is ultrasonic vibration waves (above 20 KHz) typically generated during the deformation and breaking of solid materials. It is the result of some sudden release of strain energy. Therefore, if certain stimulation is made (cutting, friction, cracking, breaking, deformation) will occur a material structural rearrangement. This rearrangement liberates deformation energy that generates elastic tension waves causing displacement in the material surface. These emitted waves propagate in solid materials with the same speed of the sound. Using a piezoelectric sensor for acoustic emission this displacement can be detected.

AE derived from metal turning consists of continuous and transient signals, which have distinctly different characteristics. Continuous signals are associated with shearing in the primary zone and wear on the rake and flank faces of the tool, while burst or transient signals result from either tool fracture or chip breakage. Therefore, plastic deformation during the cutting process in the workpiece and chip, and also contact between the tool flank face and the workpiece resulting flank wear, and the contact between tool rake face and the chip resulting in crater wear are sources of continuous AE signals. Collisions between chip and tool, chip breakage and tool fracture are examples of sources that generate transient AE signals (Xiaoli, 2002).

In a continuous-type metal cutting process where the emission generated by the deformation process is continuous (e.g. orthogonal machining), an appropriate method for analysis of AE signal is based on the Root Mean Square (RMS) signal value. Earlier correlations between the emission signal and parameters of the metal cutting process were based on the mean RMS value (Kannatey–Asibu and Dornfeld, 1981), since the instantaneous RMS value of the signal changes with time. However, the utilization of mean RMS value to monitor the cutting process is adequate since the source and sensor positions are not changed. The level of the d.c. equivalent, or the mean RMS amplitude, is sensitive to both source and sink locations (Kannatey-Asibu and Dornfeld, 1982).

According to Liang and Dornfeld (1987), the frequency range of the AE signal goes from 50 KHz to 1000 KHz approximately, which is above the mechanical vibrations range or involved noises in a machining process. This is one of the main advantages of the AE signal in tool wear monitoring, since it is relatively simple to eliminate noises using high pass band and low pass band filters. The extreme sensitivity of AE signals also provide and efficient and reliable method to be used to monitor cutting operations (Liu and Dornfeld, 1996).

A typical AE signal spectrum from a cutting operation normally consists of continuous and transient signals. The continuous signals are associated with the mechanics of chip formation, i.e., shearing in the primary shear zone, but is also affected by tool wear. The transient signals results form phenomenon like tool failure, chip breakage or collisions with tool or workpiece. However, the contact between chip and tool, and workpiece and tool is the most important source of AE signals in a continuous cutting operation like turning. This is the reason why the AE signal is used more specifically to monitor tool wear. Dolinsek and Kopac (1999) after investigations on turning operation using coated carbide tools concluded that tool wear is one of the most influential factors contributing to an increase in the energy of the AE signal.

According to Xiaoli, (2002), Lan and Dornefeld (1983) and Iwata et al (1977), the AE signal intensity increases linearly with cutting speed, it is little affected by depth of cut and decreases with feed rate and tool rake angle. Tool wear increases the intensity of the AE signal and affects directly the generated surface roughness, because the contact area between chip and tool increases.

A machined surface is the result of a process that involves plastic deformations, rupture, elastic recovery, heat generation, vibration, residual stresses and chemical reactions sometimes (Machado and Da Silva, 2004). The roughness depends on many factors, amongst them the machining parameters, tool geometry, workpiece geometry, machine tool rigidity, workpiece material and tool material (Nakayaman et al, 1966; Shouckry, 1982). Some of the factors affecting roughness are also sources of AE signals.

The objective of this work is to correlate the AE signal with the workpiece roughness profile. The AE is measured during the cutting process and the RMS of the signal is correlated to a parameter that represents the machined surface roughness.

2. Experimental Procedure

The experiments of this work were carried out in an IMOR PRN-320 conventional lathe. The workpiece material was an AISI 1045 carbon steel with average hardness of 206 HB in a cylindrical bar shape, with 160 mm of length and 65.80 mm of diameter.

The equipment for acoustic emission signal sensing consists of an AE sensor, a signal-processing unit DM 42 with 4 channels, a signal processing unit source and a virtual instrument by LabVIEW. The equipment is connected to an acquisition card NI-DAQ PCI-6035E, and a computer to store the signal. A trigger is used to synchronizing the workpiece rotations with the EA signal acquisition to allow the identification of the acquired signal for each workpiece revolution. The trigger consists of a light source that is reflected by a little mirror located in the lathe chuck and captured by a light sensor led in the other extremity. Figure 1 shows the experimental set-up used in this work.

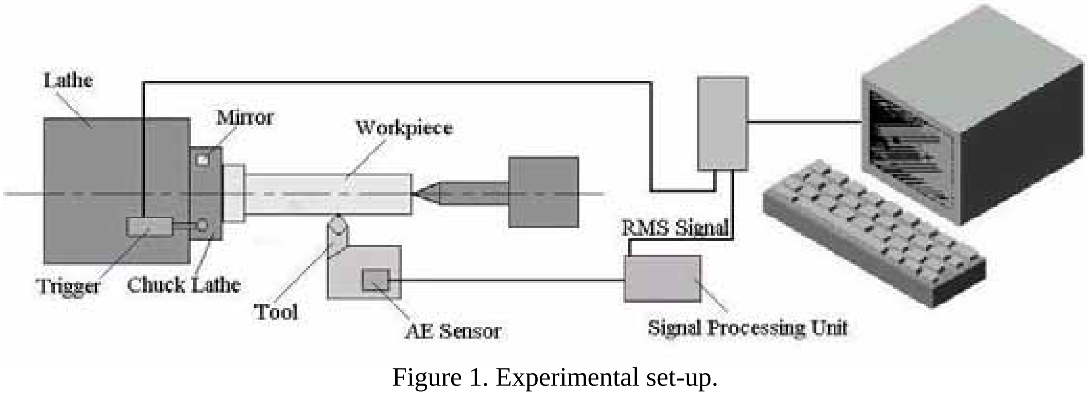

Figure 1. Experimental set-up.

In order to facilitate the localization of the AE signal acquired during each rotation, a gap of 10 mm width and 10 mm depth was machined throughout all the workpiece length, as shown in Fig. 2. The workpiece surface roughness was measured using a Mitutoyo SJ 201P stylos profilometer.

Figure 2. AISI 1045 carbon steel workpiece material.

It was used a constant spindle rotation of 618 rpm which means that for the initial workpiece diameter of 65.80 mm the cutting speed was 125.81 m/min, and for the final diameter of 64.80 mm the cutting speed was 127.65 m/min. The depth of cut (ap) was 0.50 mm and feed rate (f) 0.079 mm/rev. It was used coated cemented carbide grade inserts with specification SPUN 12 03 08, ISO P35 grade mounted in a tool holder ISO CSBPR 2020 K12.

Figure 3 shows a typical AE signal acquired during one workpiece rotation. For this emission signal graph it is observed a region when the tool crosses the workpiece gap, when the acoustic emission signal drops to zero because the tool looses contact with the workpiece. This region is a reference point to measure the surface roughness. Only one value (RMS value) is used from such graph, the one that corresponds to the AE signal in the region of the workpiece where the surface profile is measured. For this work, it is used an average of five points in the neighbourhoods of the analysed region. An AE signal graph like the one show in Fig. 3 is acquired for each workpiece rotation. As the surface profile was measure in a length of 4 mm (it was used a cut-off of 0.8 mm), it means that it is necessary fifty AE graphs (it is necessary 50 rotations for the tool to travel 4 mm in the feed direction according to the spindle rotation and the feed rate selected). Each AE graph contains approximately 400 points, because of the acquisition rate selected.

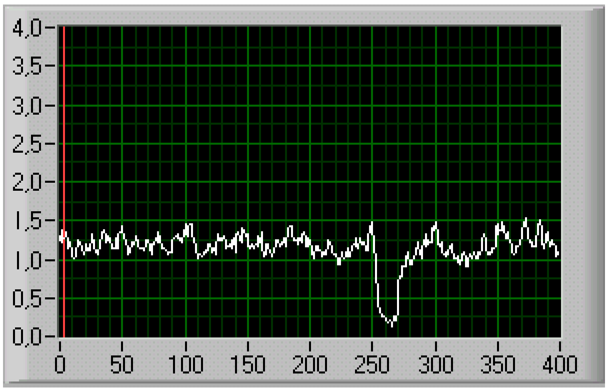

Figure 3. AE signal behaviour during cutting.

In order to produce different surfaces profiles, two cemented carbide tools were use, one with a maximum flank wear (VB_{Bmax}) close to 0.30 mm, and a new cutting edge with no flank wear. It was done six tests for each tool, at the same cutting conditions.

3. Experimental Results and Discussion

The surface profile is composed of some events, amongst them the feed marks in accordance with the tool geometry. These marks would form a theoretical surface, which the profile could be foreseen. However, the real profile deviates from the theoretical due to the system vibrations, burrs, side flow, built-up edges particles and wear or damages of the cutting edge.

The acoustic emission signal is composed of plastic and elastic deformations that occur during the chip formation and others phenomena. Therefore, even if it was possible to obtained a theoretical machined profile, the AE signal measured during this operation, measured according to the experimental procedure proposed here, could not represent the roughness profile. However, the AE signal could indicate others phenomena that contribute to form the profile. Thus, it would be interesting to analyse the roughness profile to look for alterations in relation to the theoretical profile and, if possible to identify amongst these alterations, which could be detected by the AE signal graph.

Figure 4 presents the complete acoustic emission signal during one of the tests. The reduction of the AE signal is easily observed, tending to zero, when the tool crosses the workpiece gap. The graph contains about 32000 acquired points, 400 points for each workpiece rotation. This graph corresponds to an acquisition time after 80 workpiece rotations, which corresponds to one test.

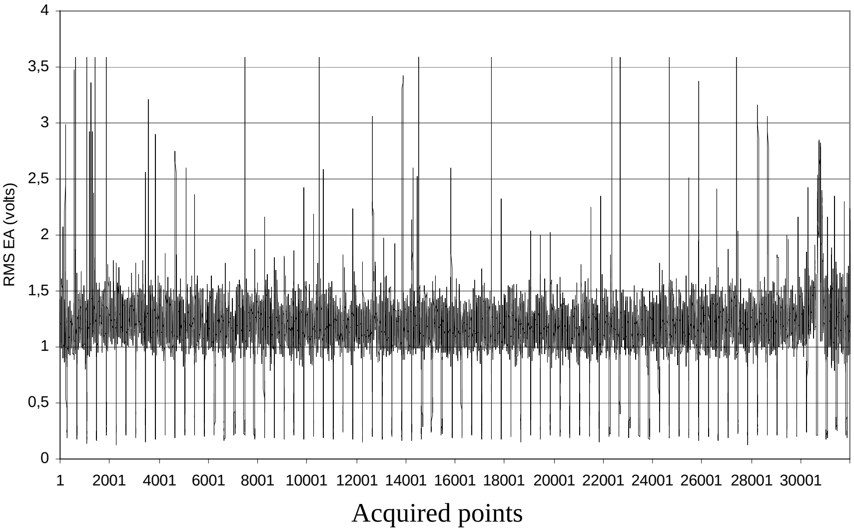

Figure 4. Acoustic emission signal for one test.

Diniz et al (1992) used a frequency range between 200 KHz and 300 KHz in his experiments with AE on turning operations to analyse the frequency spectrum. In this work it was used only the high pass-band filter of 100 KHz. This was because the equipment limitations used in this experiment. It was acquired only the RMS of the signal. Therefore any information of the spectrum correspond to a short cutting time.

Figure 5 shows the corresponding part of the entire graph of Fig. 4 for the first 1000 acquired points. This graph allows a better observation of the behaviour of the AE signal during the machining. The workpiece region where the roughness profile was acquired corresponds to a region between points 315 and 319 of Fig. 5 and is determined using the gap as reference.

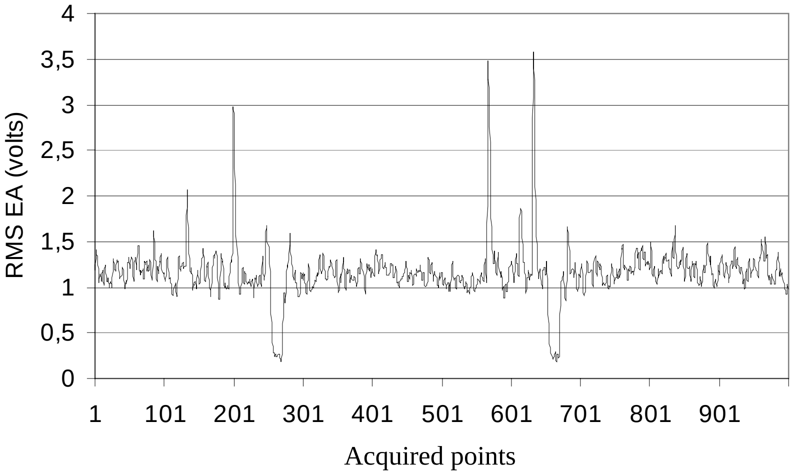

Figure 5. AE signal for the first 1000 points in one test.

The instantaneous AE RMS signal that would correspond to the beginning of the stretch where the roughness profile was acquired, is the average from points 315 to 319. The result is an average value of 1.034 V (AE_{RMS}). Using the same procedure for the second workpiece rotation, the average from points 715 to 719 results in a value 1.1284 V. Repeating this procedure for all rotations needed to complete the 4 mm length, the graph shown in Fig. 6 is obtained.

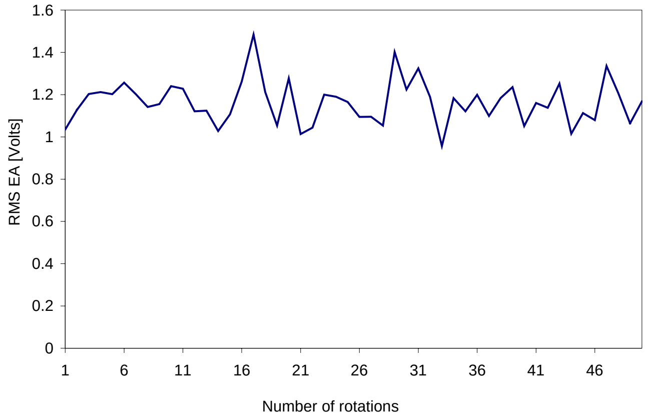

Figure 6. AE signal for one of the tests obtained in the same stretch where the roughness is measured.

Figure 7 shows the measured surface profile for the corresponding test of Fig. 6.

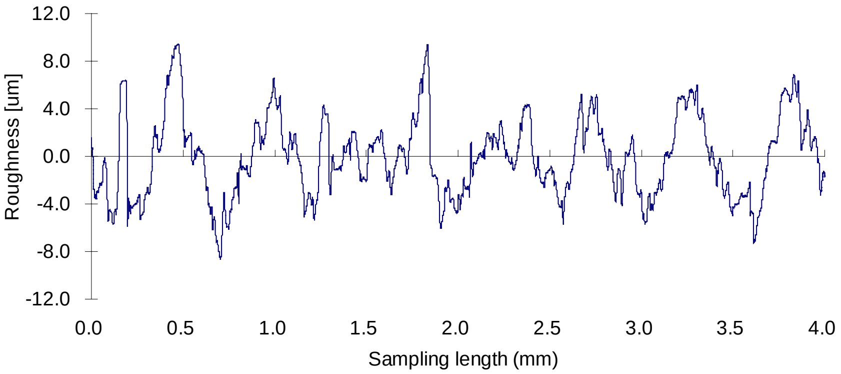

Figure 7. Surface profile obtained in the test corresponding to figure 6, this is the test $A_{1.1}$.

A direct comparison between Figs. 6 and 7 is not possible. While the first graph represents 50 points from the AE signal, the second represents about 8000 points from the surface profile. It is necessary then to use a parameter that represents the two graphs and to compare their values. Innumerable parameters can be used to evaluate the roughness of a machined surface. Amongst them the parameter Ra is the main one. This is the universally recognized and most used parameter of roughness (Whitehouse, 2002). However, although it is so popular, the Ra roughness is not a good parameter for statistical works. This parameter does not give much information about the surface characteristics of a component under test. Also, quite different surfaces can have exactly the same Ra value, consequently perform in a different manner. Kurtosis (R_{ku}) and skewness (R_{sk}) are other parameters that can be used to evaluate a surface profile, although they are not commonly used.

The parameter kurtosis (R_{ku}) provides a means to measure the sharpness of a surface profile, with a spiky surface exhibiting a high numerical value of R_{ku}. Alternatively, a bumpy surface topography will have a low R_{ku} value. As a consequence of this ability to distinguish variations in the actual surface topography, R_{ku} is an useful parameter in the prediction of in-service component performance with respect to lubricant retention and subsequent wear behaviour for example. If the amplitude distribution curve of a surface profile has a balanced Gaussian shape, the value of R_{ku} for this surface approximates to the value 3. A bumpy surface will give a value less than 3 and a peaky or spiky surface a value more than 3.

The experimental values of RMS of the AE, Ra, R_{sk} and R_{ku} obtained for the machined surfaces are shown in Tab. 1. These values were obtained repeating the procedure used to make Fig. 6, for all acquired values. This table was created for all tests. Tests A are for the worn cutting tool, while tests B are the experiments with the new cutting edge.

Table 1 – Average RMS AE signal, Ra, Kurtosis and Skewness.

Test	AE signal (RMS)	R_{ku} roughness (µm)	R_{sk} roughness (µm)	Ra roughness (µm)
$A_{1.1}$	1,167	-0,2624	0,2801	2,74
$A_{1.2}$	1,133	-0,4070	0,1099	2,15
$A_{1.3}$	1,166	-0,1409	-0,2486	1,62
$A_{2.1}$	1,185	1,9813	0,9724	5,62
$A_{2.2}$	1,246	0,3086	0,4679	4,40
$A_{2.3}$	1,355	3,0227	0,6262	3,28
$B_{1.1}$	1,400	0,1250	0,2601	2,38
$B_{1.2}$	1,727	0,6999	0,0948	1,47
$B_{1.3}$	2,163	7,1876	2,0529	2,86
$B_{2.1}$	1,241	0,0871	-0,4263	2,09
$B_{2.2}$	1,259	0,2653	-0,4718	2,37
$B_{2.3}$	0,725	0,0157	-0,4179	2,47

Using the previous table data it is possible to construct a graph representing the relationship between the measured roughness parameters and the AE RMS signal. Figure 8 shows the relationship between the kurtosis and the AE RMS signal for all the cutting conditions and both cutting tools.

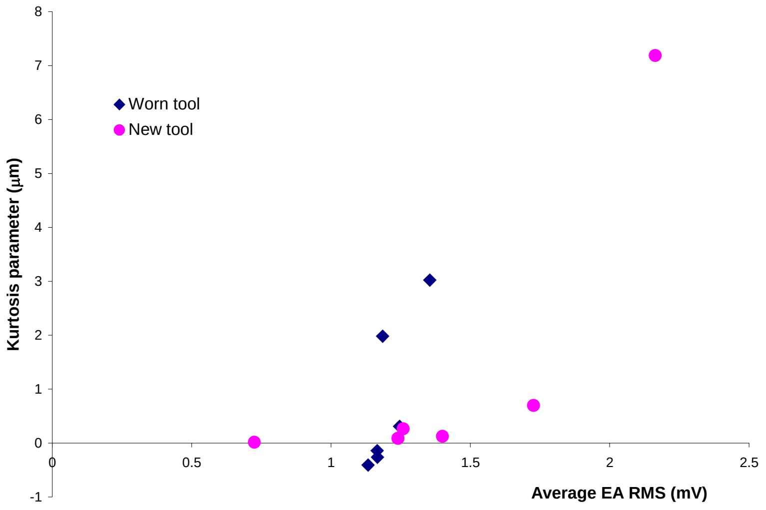

Figure 8. Average AE_{RMS} *vs.* kurtosis parameter.

The previous graph clearly shows that acoustic emission signal tends to increase with the R_{ku} parameter of the machined surface roughness profile when a new tool is used. The AE signal seems to be more sensible for values of R_{ku} more than 1.

If the cutting conditions are not changed, the variation of the acoustic emission level during the machining is related with the variation of the released energy of its sources. The main sources would be: discordances movement, phase transformations, cracking formation and friction mechanisms (Liptai et al, 1972). Probably, the three first sources are not applied in the variation of the RMS level of the signal during the machining. The last source, the friction mechanisms, is the one that can be responsible to the effect on the signal by tool wear.

However, the relationship between roughness and acoustic emission is influenced by the relationship between tool wear types and acoustic emission. Flank wear is the most common type of wear in the cutting tools used in these experiments. When this wear increases, the contact area between workpiece and tool also increases. This increases the friction in the contact region between the secondary clearance face of the tool and the machined surface. According to Pigari and Diniz (1996), the AE_{RMS} signal level increases substantially when the end of the tool life is closely. As the increasing of the maximum tool flank wear is associated with changes in the surface roughness (normally increasing it) and the AE signal (also increasing), it could be possible to associate roughness level generated in the worpiece with the AE level. However, the tool that contained initial wear did not present a clear correlation between AE signal and the parameter R_{ku}.

For the two initial conditions of the tool wear, kurtosis presented the majority of the values below three. It indicates that the generated surface was more flattened.

Another roughness parameter that can represent the profile of a machined surface is the skewness (R_{sk}). The skewness is derived from the amplitude distribution curve, representing the symmetry about the mean line. This parameter indicates whether the spikes on the surface are predominately negative or positive or if the profile has an even distribution of peaks and valleys. Figure 9 shows the relationship between R_{sk} and the AE signal for the results of this work. It is also observed a tendency of increasing AE signal (as previous calculated) with the increase of the R_{sk} value for the new cutting edge. It means that with an increase of the AE the surface profile changes from predominance of valleys for another one with predominance of peaks. When a worn tool is used, there is no obviously relationship between the two signals, and the generated surface profile is predominantly composed by peaks. It is interesting to note that the parameters R_{sk} and R_{ku} are both indicated when it is necessary to distinguish the roughness profile for surfaces with the same value of Ra.

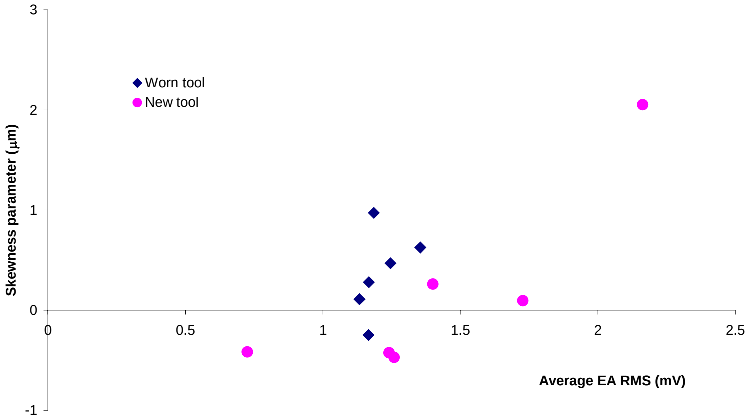

Figure 9. Average AE_{RMS} *vs.* skewness parameter.

It is also interesting to observe that there is no correlation between the AE signal and the Ra roughness (values shown in the Tab. 1) for both new and worn cutting edge, as shown in Fig. 10. In this in case, the Ra roughness seems to be not affected by the responsible phenomena for the variations on AE signal. It is also interesting to note the difference in the graph between new and worn tool. While the new cutting edge presented a wide range of AE signal for small variation on the Ra parameter, the worn cutting edge presented a wide variation on the Ra parameter for a small variation on the AE signal. This can be an indication of the effect of wear on the signal of acoustic emission.

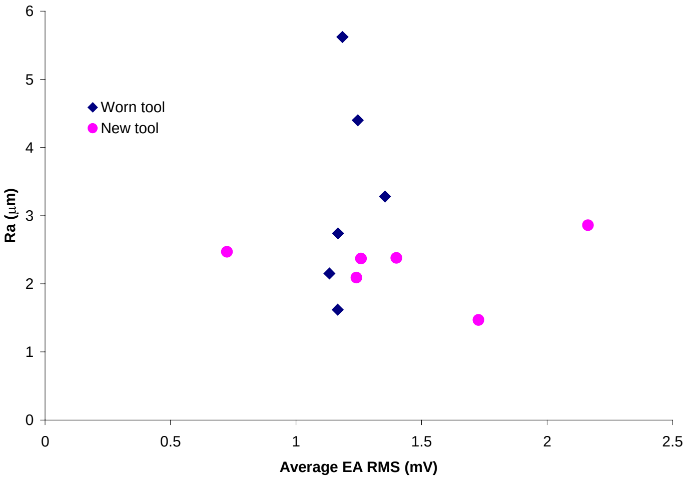

Figure 10. Average AE_{RMS} *vs.* Ra parameter.

4. Conclusions

The results obtained allow the following conclusions to be withdrawn for the cutting conditions and materials adopted in this work:

1. There is no correlation between the AE signal and the roughness parameter Ra;
2. The new tool presented a good correlation between the R_{ku} and R_{sk} parameters with the AE signal. When both parameters increase, the AE signal also increases.
3. The worn tool did not show a good correlation between the R_{ku} and R_{sk} parameters with the AE signals.

5. Acknowledgements

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