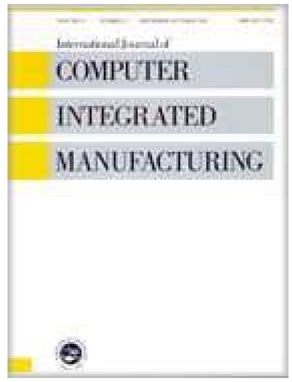
(Special Issue Responsive Manufacturing) - Application of multi-sensor signals for monitoring tool/workpiece condition in broaching.

Fathi Boud, N N Z Gindy



(Special Issue Responsive Manufacturing) - Application of multi-sensor signals for monitoring tool/workpiece condition in broaching.

Journal:	*International Journal of Computer Integrated Manufacturing*
Manuscript ID:	TCIM-2006-IJCIM-0078.R1
Manuscript Type:	Special Issue Paper
Date Submitted by the Author:	22-Sep-2006
Complete List of Authors:	Boud, Fathi; The University of Nottingham, School of Mechanical, Materials and Manufacturing Engineering Gindy, N N Z; The University of Nottingham, School of Mech, Materials & Man Eng'g
Keywords:	METAL CUTTING, TOOL CONDITION MONITORING, TOOL WEAR, ACOUSTIC EMISSION, PROCESS MONITORING
Keywords (user):	turbine disc, responsiveness

International Journal of Computer Integrated manufacturing, Vol. X, No. X, Month 2006, xxx-xxx

Application of multi-sensor signals for monitoring tool/workpiece condition in broaching

F. BOUD*, N. GINDY

School of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

Process monitoring can be used for improving machining reliability and failure prediction. As manufacturing anomalies are a potential cause of gas turbine disc failure in aero-engines, Engine life and performance can be improved by developments of manufacturing anomaly detection. The paper identifies appropriate techniques for monitoring tool condition and surface anomalies in broaching, and presents results of the output signals obtained from multiple sensors such as acoustic emission, cutting forces, vibration, hydraulic pressure and table displacement. The results show that the signals obtained proved to be efficient in detecting surface deviations and anomalies. Tool wear was identified by the cutting force, pressure and table displacement signals. While the acoustic emission signals did not prove to be sensitive in detecting tool wear, they were efficient in detecting surface anomalies such as smearing, scoring and overheating.

Keywords: Process monitoring, broaching, acoustic emission, wear, turbine disc

1. INTRODUCTION

Manufacturing industries today are influenced by global competition, shorter product lifecycles and increasing rates of technology change. The manufacturing community is always striving to reduce operating and product costs while trying to improve product quality and reliability. Therefore, manufacturing systems today need the ability to make a rapid and balanced response to the changing environment and demands. In order to achieve such improvements and respond to the changes, industries such as aerospace manufacturers require systems that are flexible, responsive and reconfigurable. In order to meet the responsive aerospace industry needs of the future, improvements need to be made not only to the products themselves, but also to the processes by which they are created.

In recent years the surface quality of machined parts has become increasingly important. The surface condition of a workpiece affects the service life, appearance and function of the component. Thus, surface quality becomes a critical element in the production process, particularly in the aerospace industry where safety is a significant issue.

* Corresponding author. Email: fathi.boud@nottingham.ac.uk

Broaching is widely used in the gas turbine and aerospace industries, where difficult-to-machine materials are used extensively and the manufacture of complex profiles and the achievement of high surface integrity and geometrical accuracy are required.

The broaching tool is based on a concept unique to the process – rough, semi-finish, and finish cutting teeth combined in one tool or string of tools. A broach tool can be used to finish machine a rough surface in a single stroke. The two main characteristics of broaching are the process productivity and outstanding accuracy of the machined surface; these, combined with a high consistency of surface finish, make broaching a preferred final machining operation for the manufacture of parts with complex geometries. Since turbine discs are safety-critical components, considerable effort is expended to ensure the achievement of their safe operating life.

In comparison to other machining processes, fewer works have been published on broaching. However, there have been some experimental studies regarding the broaching process although not in the same quantity as those of other conventional processes. Some simple empirical models for surface roughness and the main cutting force versus cutting speed were proposed for internal broaching (Kuljanic 1975). While an finite element modeling approach of evaluating stress and displacement of tool and workpiece was anticipated by Viayaraghavan *et al.* (Viayaraghavan *et al.* 1981). A mechanistic model for the cutting force system under different broach geometries, process settings and workpiece conditions was developed by Sutherland *et al.* (Sutherland *et al.* 1997). Some surface quality issues for broached components have been investigated by Sajeev *et al.* (Sajeev *et al.* 2000a) concerning the influences of the deflections of the workpiece/tool fixturing systems due to cutting force variations on the geometrical accuracy of the workpiece for internal broaching. Stress distributions, obtained using finite element modeling, along the length and the depth of the workpiece, after the action of burnishing teeth have also been reported (Sajeev *et al.* 2000b). Mo *et al.* (Mo *et al.* 2005) gave suggestions for an approach to select the cutting conditions to maximize tool life while achieving the required surface quality and level of cutting forces in broaching of heat-resistant alloys.

On a conventional machine tool, the operator decides the number of cuts, time for machining or when a tool has reached a condition such that it has to be changed. However, on unmanned machining systems, the decision about when a tool needs to be replaced has to be automated. **Sensor** systems are increasingly playing a pivotal role in tool condition monitoring.

The research on sensors and systems for tool condition monitoring has been developing extensively over a number of years. The use of a large variety of sensors in the monitoring of machining processes represents an important step towards the reduction of poor quality and hence reduction of costs.

Several reviews have been published concerning the developments and trends in monitoring of machining processes (Tlusty *et al*. 1983, Tonshoff *et al*. 1988 Byrne *et al*. 1995). A large amount of research has been carried out on tool condition monitoring using single **sensor** signals such as acoustic emission (Diniz *et al*. 1992, Ravindra *et al*. 1997, Inasaki 1998, Tansel *et al*. 1998, Dolinšek *et al*. 1999, Chiou *et al*. 2000, Govekar *et al*. 2000, Srinivasa Pai *et al*. 2002, Lee *et al*. 2006), cutting forces (Lin *et al*. 1996, Ertunc *et al*. 2004, Kuljanic *et al*. 2005, Milfelner *et al*., 2005), vibration (Bonifácio *et al*. 1994), and cutting power (Dimla *et al*. 2000). In addition, an increasing amount of research is taking place with multi-sensor systems, as these can contribute to the accomplishment of higher machining precision (Barrios *et al*. 1993, Ruiz et al. 1993, Noori-Khajavi *et al*. 1995, Yan *et al*. 1995, Dimla *et al*. 2000, Kang *et al*. 2001, Scheffer *et al*. 2001, Jantunen 2002, Chung *et al*. 2003, Haber *et al*. 2004). **In terms of broaching, a multi sensor inspection system for a broach tooth shape was developed by Xiang et al. (Xiang 2002) in order to ensure the quality of broach sharpening and determine when to sharpen a broach.** However, few studies have reported on the monitoring of workpiece surface quality (Wang *et al*. 2001, Tonshoff *et al*. 2000) **and more specifically in broaching (Axinte *et al*. 2004, Axinte *et al*. 2005).**

Tool wear is a complex phenomenon occurring in different and various ways in metal cutting processes. Generally, worn tools adversely affect the surface finish of the workpiece and therefore there is a need to develop tool wear condition monitoring systems which alert the operator to the state of the tool, thereby avoiding undesirable consequences. There have been many investigations regarding monitoring systems for tool wear especially in conventional machining processes such as turning (Bonifacio *et al.* 1994, Chiou *et al.* 2000, Scheffer *et al.* 2001), drilling (Liu *et al.* 1990, Al-Wardany *et al.* 1996, Abu-Mahfouz 2003), milling (Elbestawi *et al.* 1991, Lin *et al.* 1996, Sarhan *et al.* 2001, and grinding (Inasaki 1998, Fan *et al.* 2002, Couey *et al.* 2005).

The majority of tool condition monitoring research to-date has focused on conventional machining processes such as turning, drilling, milling and grinding. However, the research reported in this paper presents original work in the area of tool condition monitoring and surface anomaly detection in broaching.

This paper reports on the successful development of a process monitoring technique, **in a research laboratory with a view of extending the work to take place in industrial environments,** for monitoring broaching tool condition and detecting surface anomalies of Ti-6-4 titanium and Inconel 718 nickel base alloys, which are the dominant materials used for aerospace engines today. This development is of particular relevance to the aerospace industry, where minimising or avoiding surface anomalies can lead to benefits such as the reduction of re-manufacturing to bring the parts in the required standards.

2. EXPERIMENTAL SETUP

A retrofitted Cincinnati vertical broaching machine with a hydraulically powered ram was used for the machining of Ti-6-4 titanium and Inconel 718 nickel base alloys with a five segment broaching tool.

The monitoring system, shown in Figure 1, was used to produce the output signals of the surface deviations and detection of surface anomalies in the time domain. **The cutting speed, cutting forces, hydraulic pressure and acceleration signals were acquired at a frequency of 10 kHz, using a high speed data acquisition card (DAQ). The obtained data were analysed in time domain to identify uneven events/patterns on the output signals.**

[Insert Figure 1 here]

The monitoring system setup is shown schematically in Figure 2 with the various connections between the sensors, broaching machine and computer. The sensing system includes a cutting force dynamometer, an acoustic emission sensor, an accelerometer, a pressure sensor and a table displacement sensor.

These sensors were used as they are the most common sensors used for the types of anomalies investigated in this work. A three component (*x*, *y* and *z*) force platform dynamometer was used to measure the cutting forces. Piezoelectric sensors are particularly suited for measuring acoustic emission; with its small size it mounts easily near the source of emission and captures the signal optimally. Due to its rugged construction and the tightly welded housing, it can operate under severe environmental conditions in industry. The accelerator used for the tests, Piezoelectric triaxial, measures vibration in three mutually perpendicular axes (*x*, *y* and *z*). The pressure transducer was mounted in the hydraulic circuit which directs the movements of the broaching machine ram; it is designed to provide a high level of performance, coupled with a robust mechanical package ensuring trouble free operation under extreme environmental conditions. The displacement sensor, which measures vibration, is a non-contact analogue sensor; it uses bundled glass fibres to transmit and receive reflected light from target surface.

In order to characterise the elements of the monitoring system, pre-machining tests were performed; bump tests were carried out to stimulate the dynamometer-workpiece system by hammer impulses on the *y* and *z* directions in order to determine the natural frequencies of the system. Noise tests were carried out, with the machine idle, to identify the influence of machine tool noise on each output signal under the operating conditions.

An important aspect during the selection of suitable sensors and sensing principles is the mounting location of the used sensors. For a better signal quality, it was necessary to mount the sensors used for process monitoring as close as possible to the cutting area, which is the source of all signals. **The nearer the mounting location is placed to the cutting area the better is the signal quality in terms of higher amplitude. This may make it difficult to retrofit sensors to existing broaching machines and in some cases may make the implementation of such sensors impractical in industrial applications. There are many restrictions to mount sensors as close as possible to the cutting area. These restrictions are usually demands, that cables of the used sensors should not disturb the handling of the workpiece, the tool changing, etc. These two contrary demands have to be taken into account, in order to provide a realistic and usable test bed. Mounting location of sensors like acoustic emission or acceleration sensors is not restricted by mechanical interfaces as in the case of dynamometer tables.**

In order to identify the best location for the sensors, different locations were tested in order to evaluate the accuracy and repeatability of the output signals. The final selected locations were those that gave the best signals recorded and nearest possible position without mounting the sensors directly on the test bar when performing cutting tests.

The sensor locations are presented in Figure 2.

[Insert Figure 2 here]

In Figure 2, the positions of the sensors on the table of the broaching machine are shown in relation to the tool and workpiece. From the figure, the direction of cutting can also be seen.

3. EXPERIMENTAL PROCEDURE

The broaching tests were conducted using a five segment broaching tool symmetric along the x-axis.

The first three segments of the broaching tool are the roughing segments and the last two are the finishing segments. The profiles of the first and last tooth (T) of each of the five segments of the broaching tool and the values of the rise per tooth (RPT) in mm, which is the indentation of the cutting teeth (RPT≠0) or finishing teeth (RPT=0) are shown in Figure 3.

[Insert Figure 3 here]

As illustrated in Figure 3, the cutting edge profiles of the teeth of each segment are shown by the dotted line, where the inner line represents the cutting edge of the first tooth of the segment and the outer dotted line represents the cutting edge of the last tooth of the segment.

The tool pitch was constant at 8mm and tool edge preparation with a clearance angle 1^o and rake angle of 13^o were used, with different cutting speeds (1.8, 2.4 and 4.75 m/min) and tool wear levels (0.15 and 0.4 mm) with/without coolant (Cut-Max S-5029), to produce abusive broaching that resulted in the generation of surface anomalies and tool wear.

The values recorded for cutting force in the x-direction showed almost zero with small deviations from the zero *Fx* when blunt tools were used. The analysis focuses on the cutting force *Fy* since it was found to be highly sensitive to variation of tool condition. The analysis of the main cutting force, *Fz*, showed less sensitivity to changes in tool condition compared with *Fy*. However, *Fz* can provide useful supporting evidence in determining tool conditions. Acoustic emission is generally thought to be the most sensitive signal because it has a key advantage over other types of signals: its frequency range is far beyond that of mechanical vibrations and electrical noises, and thus these noises can be easily filtered.

Machining with a worn tool increases the fluctuations of forces on the cutting tool. Due to these fluctuations, vibrations occur in the system. Therefore, by monitoring the level of vibration, tool wear can be assessed. Particular attention is given to the vibration in the y-direction because of its influence on the accuracy and the quality of the machined surface. The machine table-workpiece-cutting tool system behaves, in certain limits of the load level, as an elastic system, which springs backward/forward according with the *Fy* variation when the teeth start/end cutting. Measurements carried out during cutting, showed that the profile deviation is mainly affected by the machine table displacement. The pressure sensor was mounted in the hydraulic circuit that commands the movement of the broaching machine ram. The hydraulic circuit is designed to vary ram pressure in reaction to variation of the main cutting force *Fz*.

In order to identify the types of severe anomalies occurring, severe overheating, material smearing and heavy scoring were produced using cutting speed of 4.75 m/min, average wear tool wear of 0.4 mm without coolant.

Material overheating was introduced by placing a shim under the segment; overheating is caused due to the severe friction generated. Scoring was produced with some teeth of the last segment chipped by electrical discharge machining. Smearing of material was produced by blocking the gullets for some teeth of the last two segments. Due to this, chip jamming

occurs between the cutting edges and the broached surface which results in material smearing.

The broached surfaces were analysed by microscopes to examine the profile deviations and anomalies and determine their concordance with the signals obtained.

3. RESULTS AND DISCUSSIONS

The results of the output signals that were obtained from multiple sensors for monitoring tool and workpiece condition and surface anomalies are presented and discussed in this section.

The output signals of the cutting force, hydraulic pressure and table displacement were effective in identifying worn cutting edges. Figures 4 (a) and (b) show examples of the cutting edge of one of the segments of the broaching tool. Figure 4 (a) shows the cutting edge of the tool where there is no wear (fresh tool), while Figure 4 (b) shows the cutting edge with some wear as examined under the optical microscope.

[Insert Figure 4 (a) here]

[Insert Figure 4 (b) here]

Tool wear is a primary factor in affecting machining processes. Monitoring of tool wear is an important requirement for realizing automated manufacturing. A worn tool can result in loss of production and reduced surface quality, thereby increasing product rejects. It has been widely established that variation in the cutting force can be correlated with tool wear. Measurement of the cutting forces can provide information on the machining conditions, which can be used to monitor the surface condition of the workpieces and wear on the cutting tools. Cutting force signals for both fresh and worn tools were obtained in order to compare the differences in results.

The time domain variation of the cutting force output signals for a fresh tool are displayed in Figure 5 (a).

[Insert Figure 5 (a) here]

In Figure 5 (a), the F_y and F_z cutting force output signals (cutting with a fresh tool) can be clearly observed for the five segments of the tool. The five bursts in signals illustrated in the graph represent when the cutting started and ended for each segment. The cutting with segment 1 ended after approximately 9 seconds, the cutting for segment 2 ended after approximately 17 seconds, for segment 3 after approximately 20 seconds, for segment 4 after approximately 32 seconds and for segment 5 after approximately 38 seconds.

The increases in signal amplitude on the graph show that the cutting forces were higher when cutting with segments 1 and 4. This is due to the cutting being performed from the top of the segments rather than the side of the segments, as in segments 2, 3 and 5, as shown in Figure 1. The signals for the cutting forces in segment 1 are higher than those for segment 4, as a result of the greater rise per tooth for segment 1 compared to segment 4.

The F_y and F_z cutting forces were found to be highly sensitive to the level of tool wear with cutting speed of 1.8 m/min with coolant, as seen in Figure 5 (b).

[Insert Figure 5 (b) here]

When comparing Figure 5 (b) with 5 (a), it is clearly observed that both the F_y and F_z cutting forces are higher in Figure 5 (b), as shown by the signals for all five segments. As in Figure 5 (a), the five bursts in the graph of Figure 5 (b) represent when the cutting started and ended for each segment, where it is also seen that the forces are higher for segments 1 and 4 than for the other three segments for the same reasons as when cutting with a fresh tool.

It is therefore clear from figures 5 (a) and (b) that there is a difference in the fluctuations of the signals when cutting with a fresh tool and a tool with some wear. Thus, proving cutting force signals are sensitive to tool wear.

The signals produced for the geometrical deviations of the tool are shown in Figure 6 for the pressure signals with cutting speed of 1.8 m/min for both fresh and tools with wear (average 0.15 mm) with coolant.

[Insert Figure 6 here]

As illustrated in Figure 6, the pressure signals for all five segments of the tool are defined by the bursts in signal in the graph. The bursts, as in the cutting forces, are evident when the cutting starts and ends for each segment. It is clearly shown that there is an increase in the pressure signals when a tool with some wear is used for all five segments, again confirming the sensitivity of the signals to tool wear.

The signals given for the geometrical deviations of the tool are shown in Figures 7 (a) and (b) for the machine table displacement vs. time with cutting speed of 2.4 m/min for both fresh and worn tools (average 0.15 mm) respectively with coolant where the sensitivity of the signals is apparent.

[Insert Figure 7 (a) here]

The levels of the signals for the machine table displacement for fresh tools are shown in Figure 7 (a). These signals can be compared to the signals in Figure 7 (b) for tools with wear.

[Insert Figure 7 (b) here]

In Figure 7 (b), the signals show when the cutting starts and ends for each of the segments. The cutting for segment 1 starts at approximately 3 seconds and ends at approximately 8 seconds, while for segment 2 the cutting ends at approximately 14 seconds, approximately 21 seconds for segment 3, approximately 25 seconds for segment 4 and approximately 29 seconds for segment 5. Comparing the graphs of Figures 7 (a) and (b), it can be seen that the signal levels are greater for the first three roughing segments in 7 (b), i.e. when cutting with worn tools. No significant difference is seen between the two graphs in relation to the last two finishing segments; this is as a result of the rise per tooth being lower and in addition being zero for the last few teeth on segments 4 and 5, when compared with the first three segments. The output signals in Figures 7 (a) and (b) show that machine table displacement signals are also responsive to tool wear.

The acceleration signal when a fresh tool is used with cutting speed of 2.4 m/min with coolant is shown in Figure 8 (a).

[Insert Figure 8 (a) here]

In Figure 8 (a) the increases in the signals represent when the cutting started and ended for each segment.

Figure 8 (b) shows the acceleration signals when a worn tool (average 0.15 mm) was used with cutting speed of 2.4 m/min with coolant.

[Insert Figure 8 (b) here]

Although the signals shown in Figures 8 (a) and 8 (b) both display differences in levels when cutting with the five different segments and between A_y and A_z, the differences in signals are not very evident between the two graphs, i.e. when cutting with fresh tools and worn tools (average 0.15 mm), with a cutting speed of 2.4 m/min with coolant. Acceleration signals, A_y and A_z, were not highly sensitive for these tests when cutting with this level of wear (average 0.15 mm) and under these cutting conditions.

The force, pressure and table displacement proved sensitive enough for performing tool condition monitoring (e.g. tool wear). However, due to their low sensitivity to material deformation, they were not capable of detecting small process malfunctions such as surface anomalies.

Optical inspection of the broached surfaces was carried out to confirm the occurrence of the anomalies, which were then related to the signals obtained.

The acoustic signal analysis techniques have been successful in confirming the existence of severe heating, material smearing and heavy scoring anomalies.

Acoustic emission signals vs. time for segments 4 and 5, the finishing segments which result in the final surface quality, of a worn tool (average 0.4 mm wear), are shown in Figure 9 (a) using cutting speed of 4.75 m/min, without coolant.

[Insert Figure 9 (a) here]

The signals in Figure 9 (a) were obtained without the generation of surface anomalies (over-heating, scoring and smearing). The increase and decrease in the signals are clearly evident from the graph for both segments 4 and 5. In order to assess the sensitivity of acoustic emission signals to surface anomalies, the signals in Figure 9 (a) can be related to the signals in Figures 9 (b) for overheating, 9 (d) for scoring and 9 (f) for smearing. The conditions for all results were obtained with a cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant for segments 4 and 5. The variations in the graphs is that the results of Figure 9 (a) were obtained without the generation of surface anomalies while the results in Figure 9 (b) were obtained by generating overheating on the surface, for Figure 9 (d) scoring was generated on the surface and for Figure 9 (f) smearing was generated on the surface.

Material overheating was generated by using a tool with an average wear of 0.4 mm and a cutting speed of 4.75 m/min without coolant. Material overheating was introduced by placing a shim under the tool segment; overheating is caused due to the severe friction generated.

[Insert Figure 9 (b) here]

The acoustic emission signals are illustrated in Figure 9 (b) after overheating conditions were introduced. When compared with Figure 9 (a), Figure 9 (b) demonstrates slightly higher level in the signals and it is not clear when the signals for segment 4 ends and those of segment 5 start which is due to the friction caused by the overheating. Severe plastic deformation and material overheating can, therefore, be detected from the signals.

Scoring was produced by broach tools with teeth chipped by Electrical Discharge Machining (EDM). The scoring was accompanied by severe material deformation as shown in the windowed section of Figure 9 (c).

[Insert Figure 9 (c) here]

The cutting conditions used to generate scoring consisted of a cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant. Figure 9 (d) shows the signals produced for the acoustic emission signals when scoring was introduced.

[Insert Figure 9 (d) here]

As seen from Figure 9 (d), when scoring is introduced to the surface, the acoustic emission signals in the graph are slightly higher than the acoustic emission signals in Figure 9 (a) where no anomalies were generated. There is no clear defined start and end of segments 4 and 5 in Figure 9 (d).

Smearing of material was produced by blocking the gullets for some teeth of the last two segments, i.e. segments 4 and 5. Due to this, chip jamming occurs between the cutting edges and the broached surface, which results in material smearing as shown encircled in Figure 9 (e).

[Insert Figure 9 (e) here]

Smearing was generated by using cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant. Figure 9 (f) shows the signals for acoustic emission during chip jamming.

[Insert Figure 9 (f) here]

It is clearly evident from Figure 9 (f) that the acoustic emission signals are at a much higher level when compared to the acoustic emission signals in Figure 9 (a). It is therefore clear that the acoustic emission signals are sensitive to the generation of smearing.

A limit for the acoustic emission signals was set and regarded as indicative of the occurrence of anomalies. The output signals were compared with the surface inspection results and were found to correlate with overheating, scoring and smearing surface anomalies.

It is apparent from the results of the signals that acoustic emission signals are sensitive to the existence of surface anomalies.

In a monitoring system, prior testing data can be input into the system to set limits for each procedure. The values would be altered for the different materials used with different machining parameters such as geometrical shapes, cutting speeds etc. so that when the target is reached the alert signals are given. The target is altered according to the needs of the requirements. The results of the tests performed show that it is feasible to set alert signals for the output signals, such as cutting forces, hydraulic pressure, machine table displacement and acoustic emission, in order to detect when tools reach certain levels of wear or end of tool life, require re-sharpening, or when certain forms of workpiece surface damage occur. Further work and tests are needed to set up a triggering technique.

This technology can be applied in the aerospace industry where it is possible to integrate sensors directly on structures to provide information regarding the tool and workpiece condition. The significance of this to the aerospace industry is of great value as safety is of primary importance, and as a result sensors and sensor systems can improve quality, reliability, productivity, costs and performance optimization in the industry.

While responsiveness is very important to the success of manufacturing firms, delivery of high quality products plays a vital role in manufacturing competitiveness. In machining processes, the cutting operation can be tightly controlled by using data collected from sensors located at different locations on the workpiece, tool, and machine-tool.

Sensor technology can aid the manufacturing industries to implement reconfigurable, reliable and cost effective manufacturing processes that can respond and be rapidly adapted to specific production and customer needs.

4. CONCLUSION

The objective of this research was to identify appropriate techniques for monitoring tool condition and surface anomalies in broaching, based on the output signals from multiple sensors. The multi-sensor system used in this investigation combined measurements of cutting forces, pressure, acceleration and acoustic emission for broaching operations.

The measurement of acoustic emission, cutting forces, acceleration, pressure and displacement signals for process monitoring were selected as they were the most suitable for detecting surface anomalies in the broaching of Ti-6-4 and Inconel 718.

Acoustic emission, cutting forces, vibration and pressure signals of the tool conditions and the surface anomalies introduced by abusive broaching were analysed. It was found that the cutting force, pressure, and machine table displacement signals were sensitive to tool condition, i.e. tool wear. The acoustic emission signals were effective in detecting surface anomalies such as smearing, scoring, overheating.

It can be concluded that, with the use of a combination of sensors, it is possible to develop techniques in process monitoring for tool condition monitoring and the identification of surface anomalies.

The advantages for using a process monitoring system can save costs for industry in the long run; these techniques, applied in industry, allow for introducing high levels of automation and guarantee the quality of the final products. By providing timely and reliable indication of the ability to detect and anticipate incipient faults at an early stage enables the operator to optimize scheduling of corrective actions so that the adverse consequences of the malfunction are minimised. The limitations of such a system can be caused by the possible mounting positions of different sensors due to convenience, wiring etc. Initial costs of the system can be a deterrent for its use, however these costs can be recuperated over time.

Rapidly evolving sensor technologies, which employ advanced techniques have the ability to greatly improve tool/workpiece condition. These sensor technologies have the potential to provide major improvements in costs, shorter lead times and improved quality and reliability through increased automation and inherent re-configurability of the monitoring system.

This work can be further extended in developing an online process monitoring system in the production line.

Acknowledgments

The authors would like thank Rolls-Royce Plc for their support and Allan Hodgson of The School of Mechanical, Materials and Manufacturing Engineering at The University of Nottingham for his encouragement, suggestions and comments.

References

Abu-Mahfouz, I., Drilling wear detection and classification using vibration signals and artificial neural network, *International Journal of Machine Tools and Manufacture*, 2003, 43(7), 707-720.

Axinte, D. Boud, F., Penny, J., and Gindy, N., Broaching of Ti-6-4 – Detection of workpiece surface anomalies on dovetail slots through process monitoring, *CIRP Annals*, 2005, 54(1) 87-90.

Axinte, D. A., Gindy, N., Fox, K., and Unanue, I., Process monitoring to assist the workpiece surface quality in machining, *International Journal of Machine Tools and Manufacture*, 2004, 44, 1091-1108.

Barrios, L.J., Ruiz, A., Guinea, D., Ibaňez, A., Bustos, P., Etxeberria, J., Experimental comparison of sensors for tool-wear monitoring on milling, *Sensors and Actuators A*, 1993, 37-38, 589-595.

Bonifácio, M.R., Diniz, A.E., Correlating tool wear, tool life, surface roughness and tool vibration in finish turning with coated carbide tools, *Wear*, 1994, 173, 137-144.

Byrne, G., Dornfeld, D., Inasaki, I., Ketteler, G., König, W., Teti, R., Tool condition monitoring (TCM) – the status of research and industrial application, *CIRP Annals*, 1995, 44(2), 541-567.

Chiou, R.Y., Liang, S.Y., Analysis of acoustic emission in chatter vibration with tool wear effect in turning, *International Journal of Machine Tools and Manufacture*, 2000, 40, 927-941.

Chung, K.T., Geddam, A., a multi-sensor approach to the monitoring of end milling operations, *Journal of Materials Processing Technology*, 2003, 139, 15-20.

Couey, J. A., March, E. R., Knapp, B. R., Vallance, R. R., Monitoring force in precision cylindrical grinding, *Precision Engineering*, 2002, 29, 307-314.

Cuppini, D., D'Errico, G., Rutelli, G., Tool wear monitoring base don cutting power measurement, *Wear*, 1990, 139, 303-311.

Dimla, D.E. Sr., Lister, P.M., On-line metal cutting tool condition monitoring. I: force and vibration analyses, *International Journal of Machine Tools and Manufacture*, 2000, 40, 739-768.

Diniz, A.E., Liu, J.J., Dornfeld, D.A., Correlating tool life, tool wear and surface roughness by monitoring acoustic emission in finish turning, *Wear*, 1992, 152, 395-407.

Dolinšek, S., Kopač, J., Acoustic emission signals for tool wear identification, *Wear*, 1999, 225-229, 295-303.

Elbestawi, M. A., Papazafiriou, T. A., Du, R. X., In-process monitoring of tool wear in milling using force signature, *International Journal of Machine Tools and Manufacture*, 1991, 31(1), 55-73.

El-Wardany, T. I., Gao, D., Elbestawi, M. A., Tool condition monitoring in drilling using vibration signature analysis, *International Journal of Machine Tools and Manufacture*, 1996, 36(6), 687-711.

Ertunc, H.M., Oysu, C., drill wear monitoring using cutting force signals, *Mechatronics*, 2004, 14, 533-548.

Fan, K. -C., Lee, M. -Z., Mou, J. –I., On-Line non-contact system for grinding wheel wear measurement, *International Journal of Advanced Manufacturing Technology*, 2002, 19(1), 14-22.

Govekar, E., Gradišek, J., Grabec, I., Analysis of acoustic emission signals and monitoring of machining processes, *Ultrasonics*, 2000, 38, 598-603.

Haber, R. E., Jiménez, J. E., Ronei Perez, C., Alique, J. R., An investigation of tool-wear monitoring in a high-speed machining process. *Sensors and Actuators A: Physical*, 2004, 116(3), 539-545.

Inasaki, I., Application of acoustic emission sensor for monitoring machining processes, *Ulrasonics*, 1998, 36, 273-281.

Jantunen, E., A summary of methods applied to tool condition monitoring in drilling. In *International Journal of Machine Tools and Manufacture*, 2002, 42(9), 997-1010.

Kang, M.C., Kim, J.S., Kim, J.H., A monitoring technique using a multi-sensor in high speed machining, *Journal of Materials Processing technology*, 2001, 113, 331-336.

Kuljanic, E., Cutting forces and surface roughness in broaching, *CIRP*, 1975, 24(1), 77-82.

Kuljanic, E., Sortino, M., TWEM, a method based on cutting forces – monitoring tool wear in face milling. In *International Journal of Machine Tools and Manufacture*. 2005, 45(1), 29-34.

Lee, D.E., Hwang, I., Valente, C.M.O., Oliveira, J.F.G., Dornfeld, D.A., Precision manufacturing process monitoring with acoustic emission, *International Journal of Machine Tools and Manufacture*, 2006, 46, 176-188.

Lin, S.C., Lin, R.J., Tool wear monitoring in face milling using force signals, *Wear*, 1996, 198, 136-142.

Liu, T. I., Wu, S. M., On-line detection of drill wear, *ASME Journal of Engineering for Industry*, 1990, 112, 299-302.

Milfelner, M., Cus, F., Balic, J., An overview of data acquisition system for cutting force measuring and optimization in milling, *Journal of Materials Processing Technology*, 2005, 164-165, 1281-1288.

Mo, S. P., Axinte, D. A., Gindy, N. N. Z., An example of selection of the cutting conditions in broaching of heat-resistant alloys based on cutting forces, surface roughness and tool wear, *Journal of Materials Processing Technology*, 2002, 160, 382-389.

Noori-Khajavi, A., Komanduri, R., Frequency and time domain analyses of sensor signals in drilling – I. Correlation with drill wear, *International Journal of machine Tools and Manufacturing*, 1995, 35(6), 775-793.

Ravindra, H.V., Srinivasa, Y.G., Krishnamurthy, R., acoustic emission for tool condition monitoring in metal cutting, *Wear*, 1997, 212, 78-84.

Ruiz, A., Guinea, d., Barrios, L.J., Befancourt, F., An empirical multi-sensor estimation of tool wear, *Mechanical Systems and Signal Processing*, 1993, 7(2), 105-119.

Sajeev, V., Vijayaraghavan, L., Rao, U. R. K., Effect of tool-work deflections on the shape of a broached hole, *International Journal of Mechanical Engineering Education*, 2000a, 28(1), 88-92.

Sajeev, V., Vijayaraghavan, L., Rao, U.R.K., An analysis of the effects of burnishing on internal broaching, *International Journal of Mechanical Engineering Education*, 2000b, 28(2), 163-173.

Sarhan, A., Sayed, R., Nassr, A. A., El-Zahry, R. M., Interrelationships between cutting force variation and tool wear in end-milling, *Journal of materials Processing Technology*, 2001, 109(3), 229-235.

Scheffer, C., Heyns, P.S., Wear monitoring in turning operations using vibration and strain measurements, *Mechanical Systems and Signal Processing*, 2001, 15(6), 1185-1202.

Srinivasa Pai, P., Ramakrishna Rao, P.K., acoustic emission analysis for tool wear monitoring in face milling, *International Journal of Production Research*, 2002, 40(5), 1081-1093.

Sutherland, J. W., Salisbury, E. J., Hoge, A model for the cutting force system in the gear broaching process, *International Journal of Machine Tools and Manufacture*, 1997, 37(10), 1409-1421.

Tansel, I., Trujillo, M., Nedbouyan, A., Velez, C., Bao, W-Y., Arkan, T.T., Tansel, B., Micro-end-milling – III – Wear estimation and tool breakage detection using acoustic emission signals, *International Journal of Machine Tools and Manufacture*, 1998, 38, 1449-1466.

Tlusty, J., Andrews, G.C., A critical review of sensors for unmanned machining, *CIRP Annals*, 32(2), 1983, 563-572.

Tonshoff, H. K., Jung, M., Mannel, S., and Rietz, W., Using acoustic emission signals for monitoring of production processes, *Ultrasonics*, 2000, 37(10), 681-686.

Tonshoff, H.K., Wulfsberg, J.P., Kals, H.J.J., König, W., van Luttervelt, C.A., Development and trends in monitoring and control of machining processes, *CIRP Annals*, 37(2), 1988, 611-622.

Vijayaraghavan, L., Krishnamurthy, R., Chandrasekaran, H., Evaluation of stress and displacement of tool and workpiece on broaching, *International Journal of Machine Tool and Design*, 1981, 21(34), 263-270.

Wang, Z., Willett, P., DeAguiar, P.R., Webster, J., Neural network detection of grinding burn from acoustic emission, *International Journal of Machine Tools and Manufacture*, 2001, 4(1-2), 283-309.

Xiang, H., Chen, J. H., Zhou, Y. F., Zhou, J., A multi-sensor inspection system based on RMOS, *International Journal of Advanced Manufacturing Technology*, 2002, 19, 448-453.

Yan, D., El-Wardany, T.I., Elbestawi, M.A., A multi-sensor strategy for tool failure detection in milling, *International Journal of Machine Tools and Manufacture*, 1995, 35(3), 383-398.

Figure Captions

Figure 1. Monitoring system setup.
Figure 2. Location of the sensors on the broaching machine table.
Figure 3. Profiles of five segment broaching tool showing first tooth (inner line) and last tooth (outer line).
Figure 4 (a) Cutting edge of a fresh tool.
Figure 4 (b) Cutting edge of a worn tool.
Figure 5 (a). Cutting force signals for fresh tools using cutting speed of 1.8 m/min with coolant.
Figure 5 (b). Cutting force signals for tools with wear, average 0.15 mm, using cutting speed of 1.8 m/min with coolant.
Figure 6. Pressure signals for fresh and tools with wear, average 0.15 mm, using cutting speed of 1.8 m/min with coolant.
Figure 7 (a). Signals given by machine table displacement for fresh tools using cutting speed of 2.4 m/min with coolant.
Figure 7 (b). Signals given by machine table displacement for tools with wear, average 0.15 mm, using cutting speed of 2.4 m/min with coolant.
Figure 8 (a). Acceleration signals for fresh tools using cutting speed of 2.4 m/min with coolant.
Figure 8 (b). Acceleration signals for tools with wear, average 0.15 mm, using cutting speed of 2.4 m/min with coolant.
Figure 9 (a). Acoustic emission signals of segment 4 and 5 using cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant.
Figure 9 (b). Acoustic emission signals for severe overheating using cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant.
Figure 9 (c). Scoring and its surface damage.
Figure 9 (d). Acoustic emission signals for scoring using cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant.
Figure 9 (e). Effect on surface of material smearing.
Figure 9 (f). Acoustic emission signals for smearing of segment 4 5 with blocked gullets using cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant.

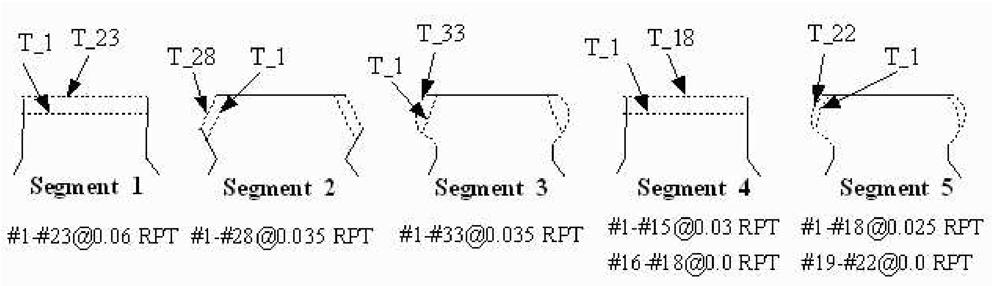


Figure 1. Profiles of five segment broaching tool showing first tooth (inner line) and last tooth (outer line).
168x48mm (96 x 96 DPI)

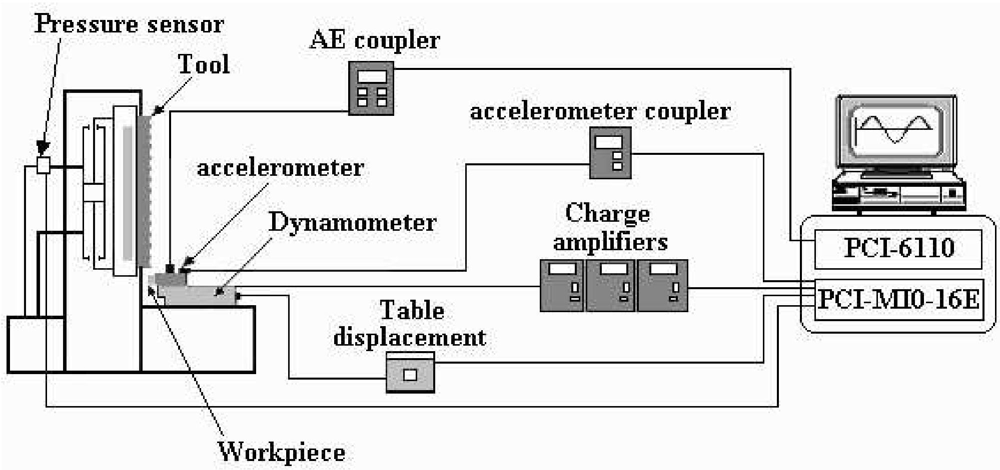


Figure 2. Monitoring system setup.
149x70mm (96 x 96 DPI)

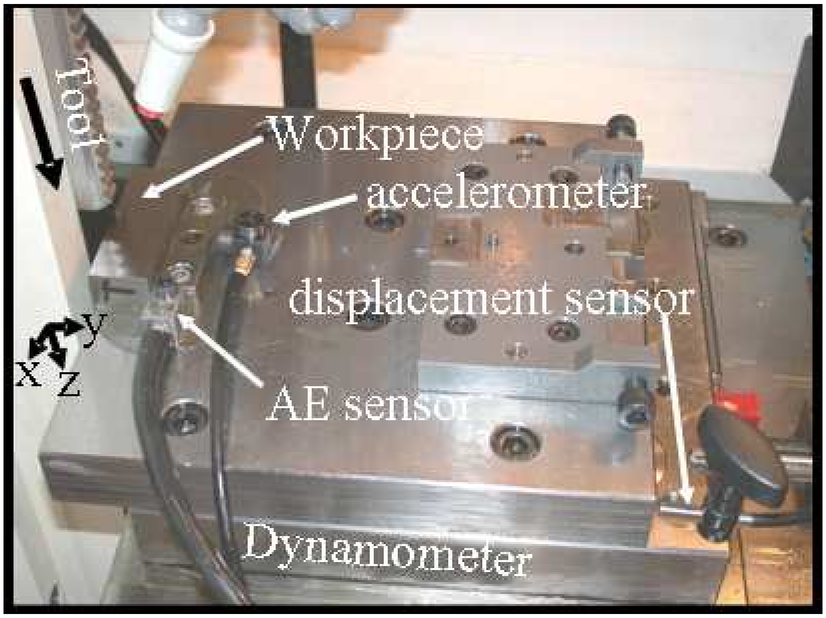


Figure 3. Location of the sensors on the broaching machine table.
69x51mm (150 x 150 DPI)

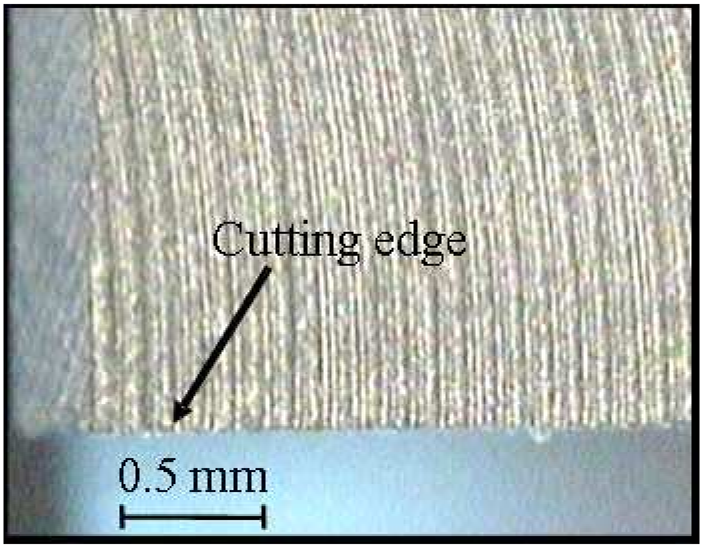


Figure 4 (a). Cutting edge of a fresh tool.
58x45mm (150 x 150 DPI)

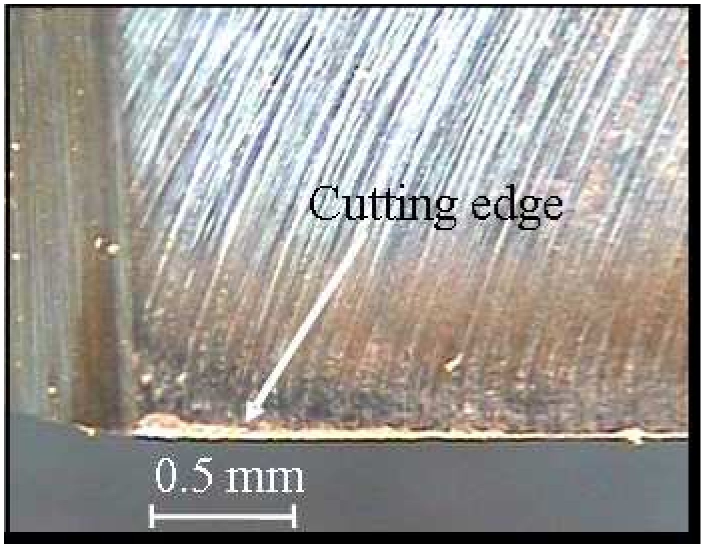


Figure 4 (b). Cutting edge of a worn tool.
58x45mm (150 x 150 DPI)

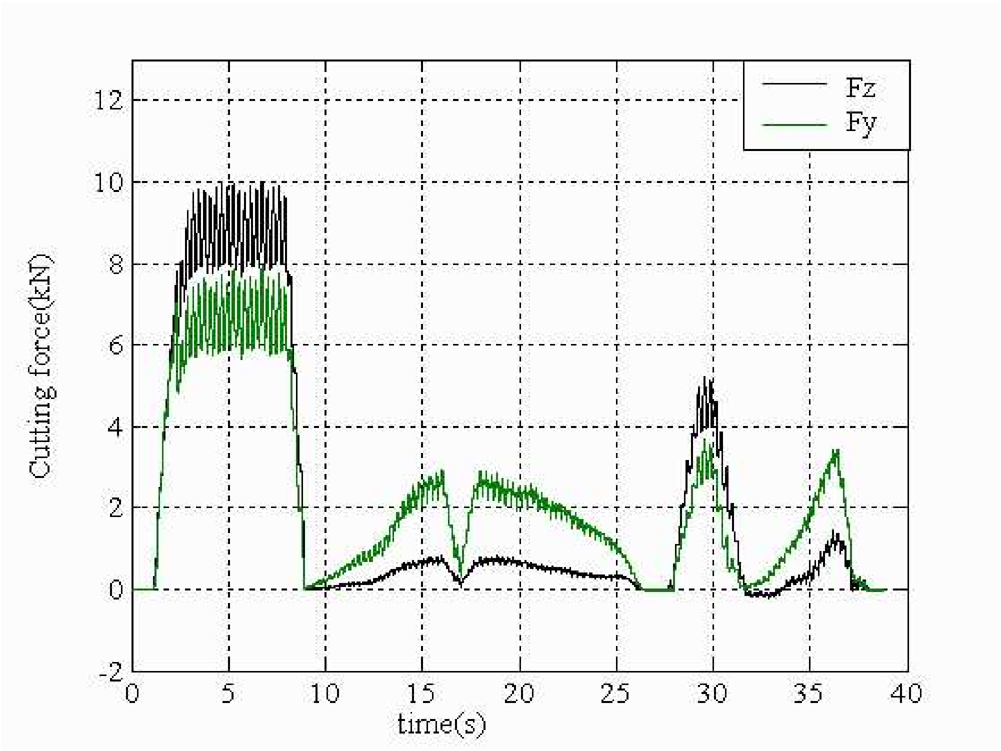


Figure 5 (a). Cutting force signals for fresh tools using cutting speed of 1.8 m/min with coolant.
148x111mm (96 x 96 DPI)

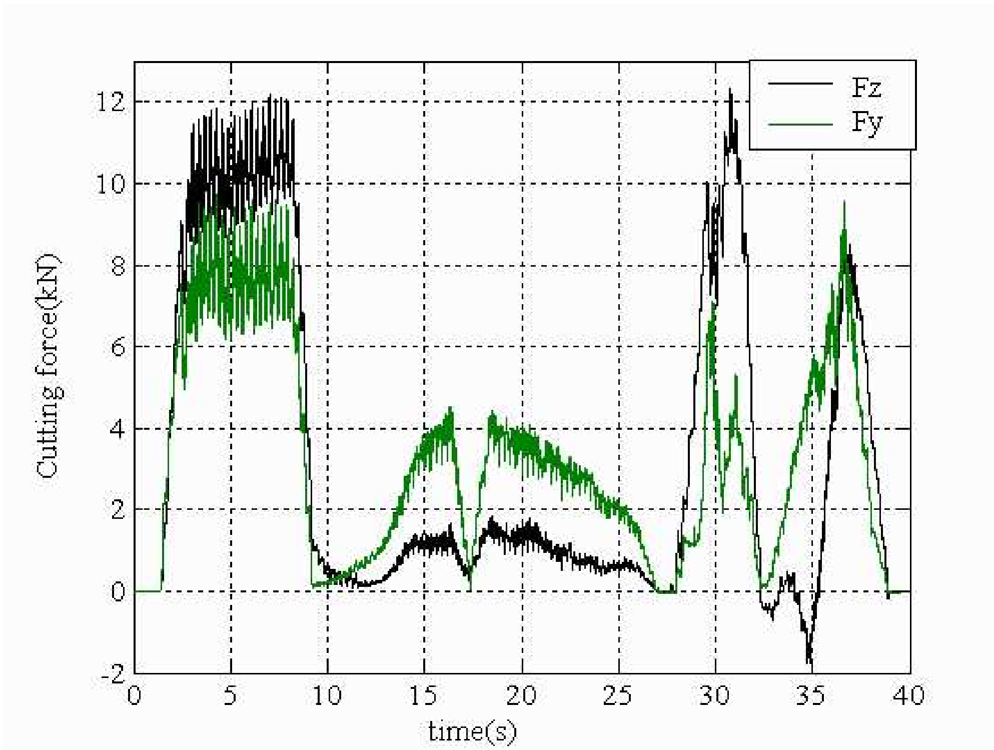


Figure 5 (b). Cutting force signals for tools with wear, average 0.15 mm, using cutting speed of 1.8 m/min with coolant.
148x111mm (96 x 96 DPI)

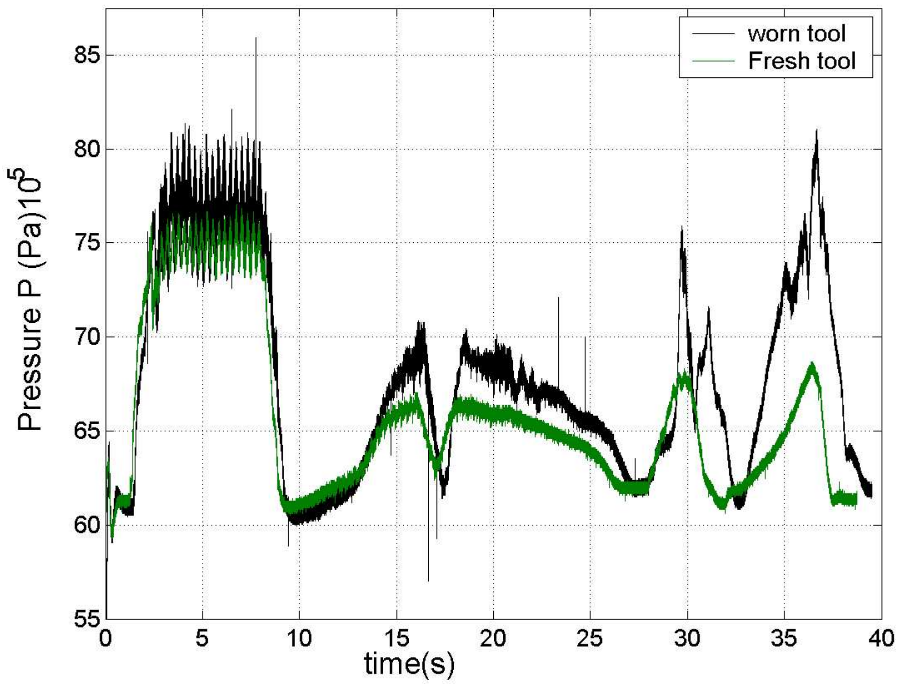


Figure 6. Pressure signals for fresh and tools with wear, average 0.15 mm, using cutting speed of 1.8 m/min with coolant.
203x152mm (150 x 150 DPI)

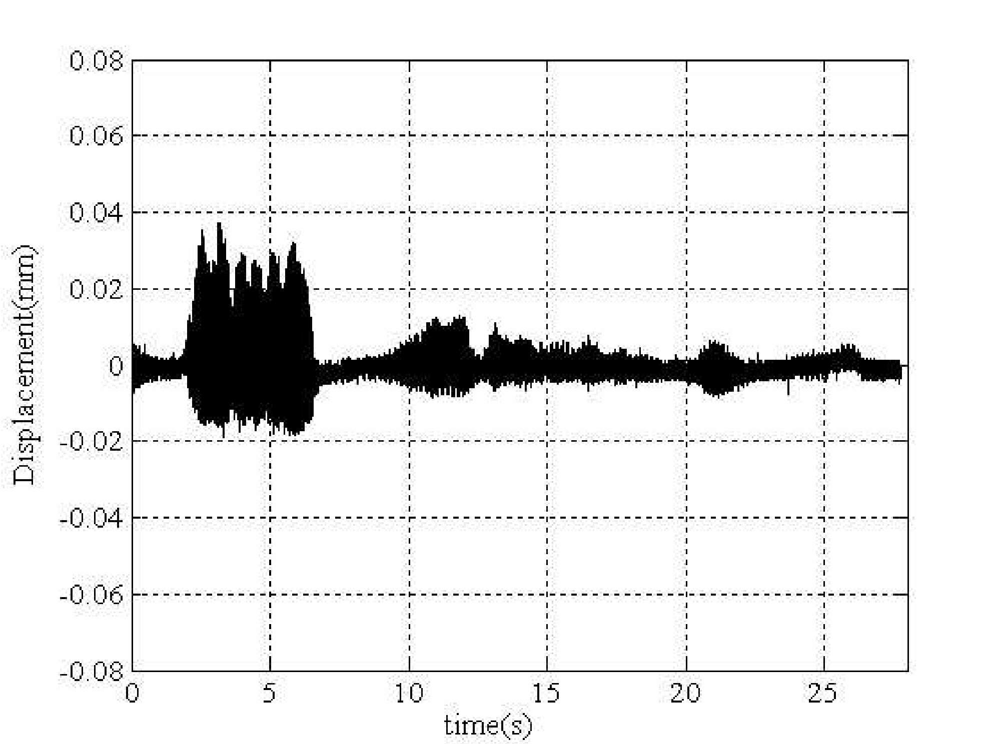


Figure 7 (a). Signals given by machine table displacement for fresh tools using cutting speed of 2.4 m/min with coolant.
148x111mm (96 x 96 DPI)

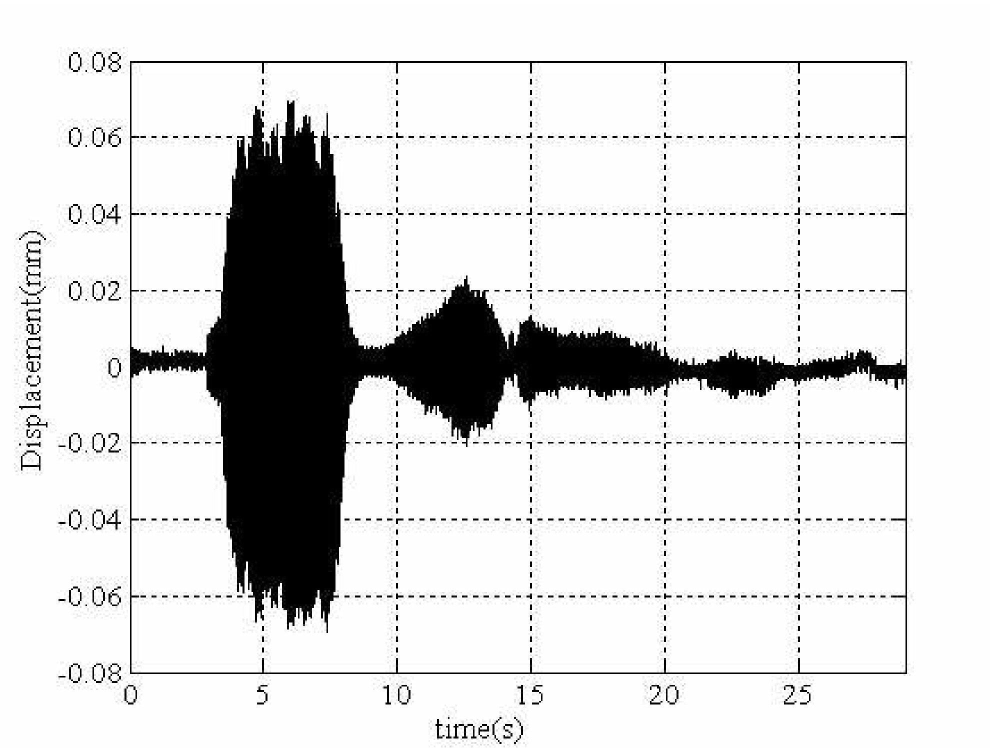


Figure 7 (b). Signals given by machine table displacement for tools with wear, average 0.15 mm, using cutting speed of 2.4 m/min with coolant.
148x111mm (96 x 96 DPI)

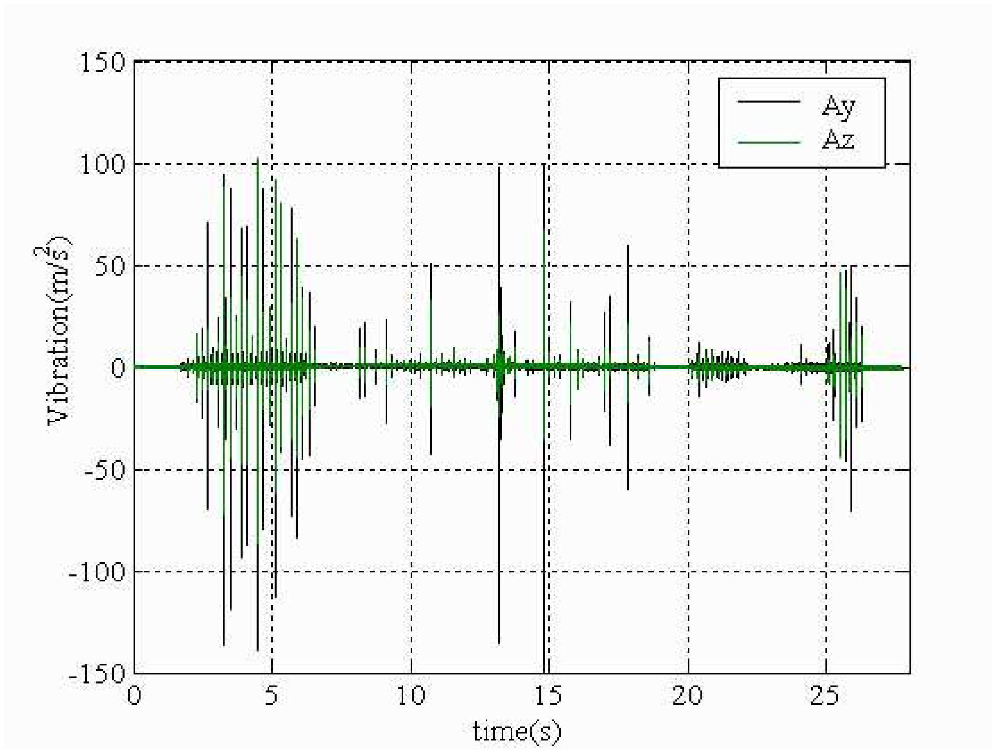


Figure 8 (a). Acceleration signals for fresh tools using cutting speed of 2.4 m/min with coolant.
148x111mm (96 x 96 DPI)

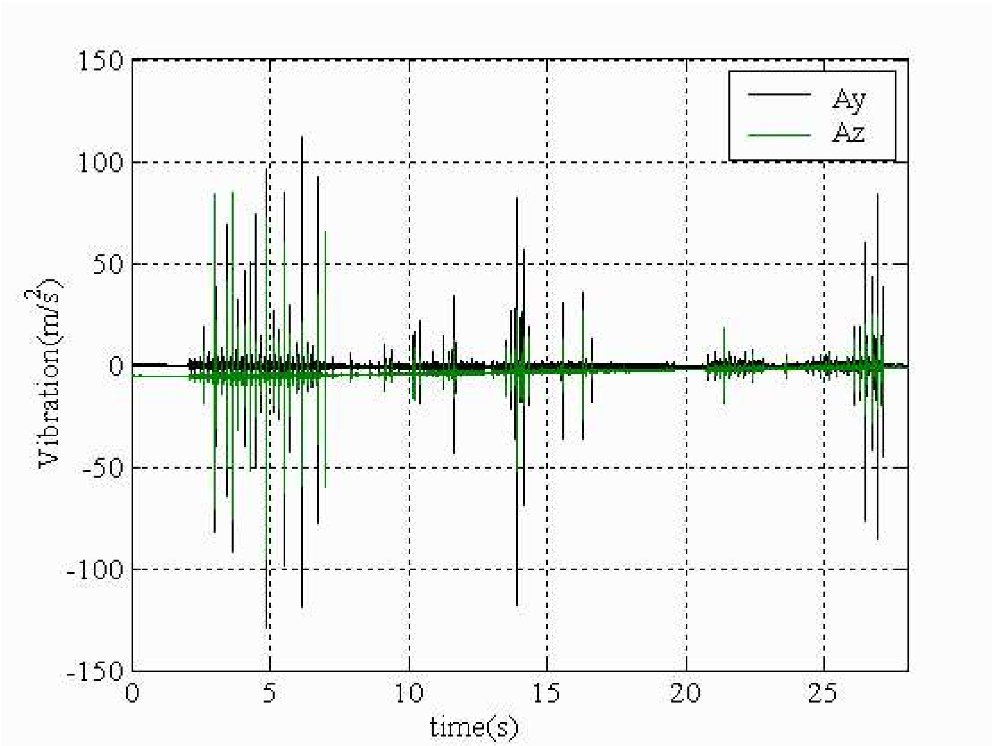


Figure 8 (b). Acceleration signals for tools with wear, average 0.15 mm, using cutting speed of 2.4 m/min with coolant.
148x111mm (96 x 96 DPI)

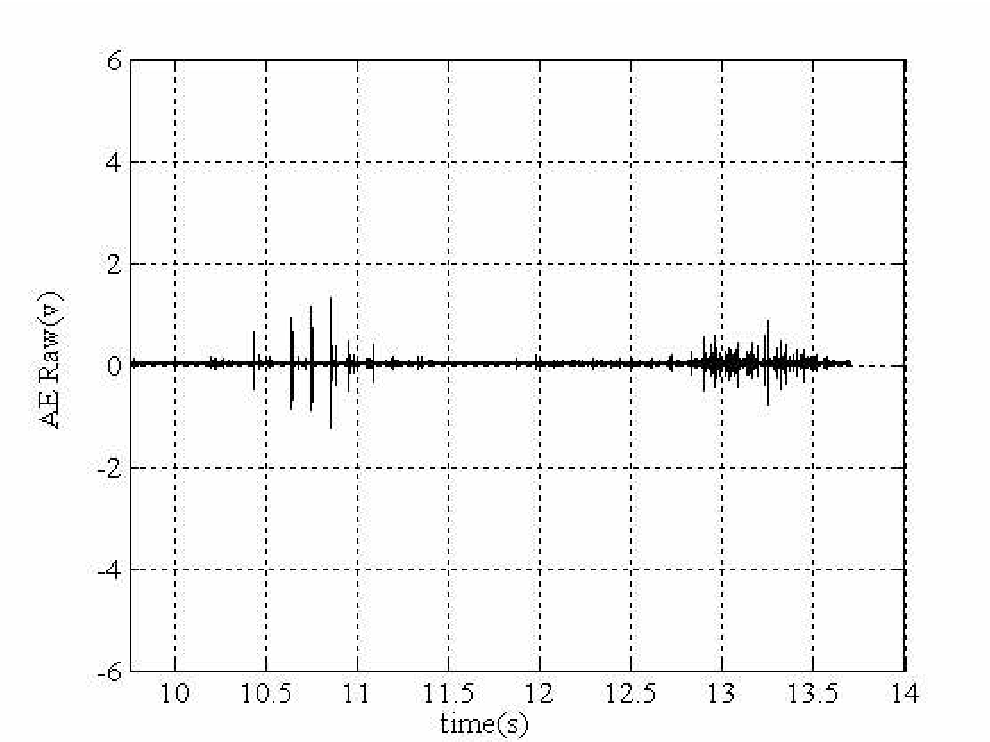


Figure 9 (a). Acoustic emission signals of segment 4 and 5 using cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant.
148x111mm (96 x 96 DPI)

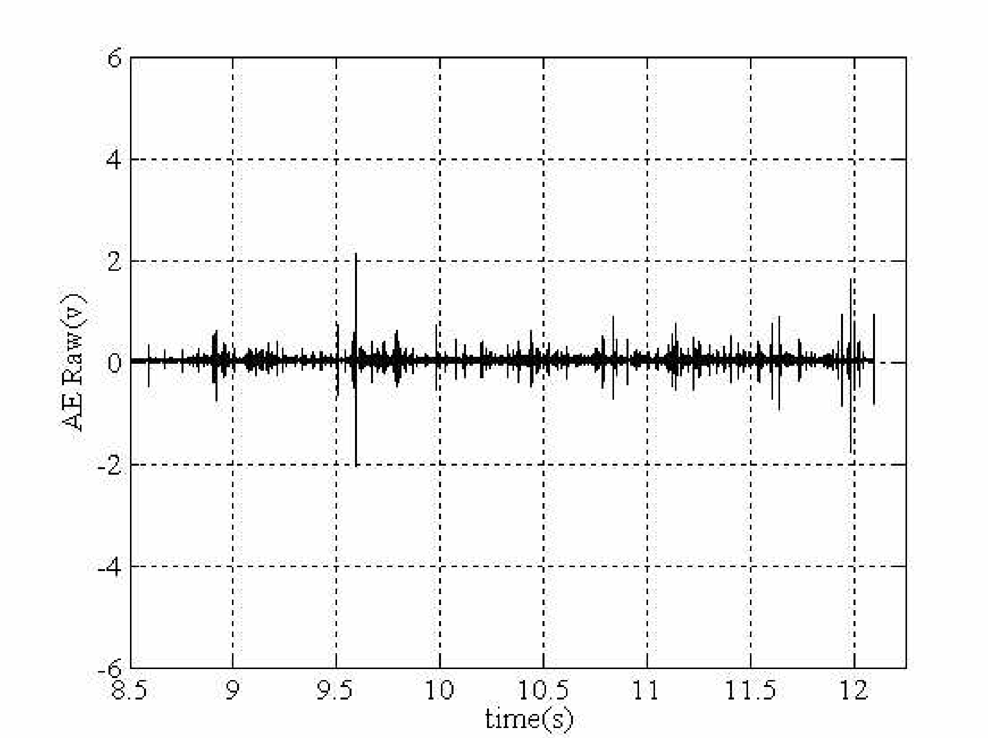


Figure 9 (b). Acoustic emission signals for severe overheating using cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant.
148x111mm (96 x 96 DPI)

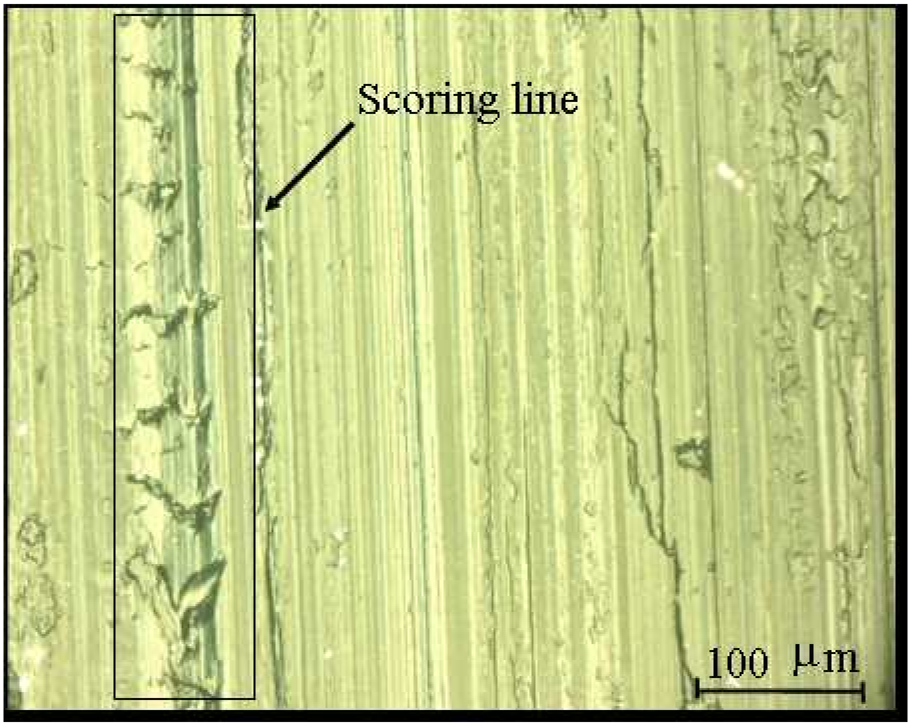


Figure 9 (c). Scoring and its surface damage.
76x60mm (150 x 150 DPI)

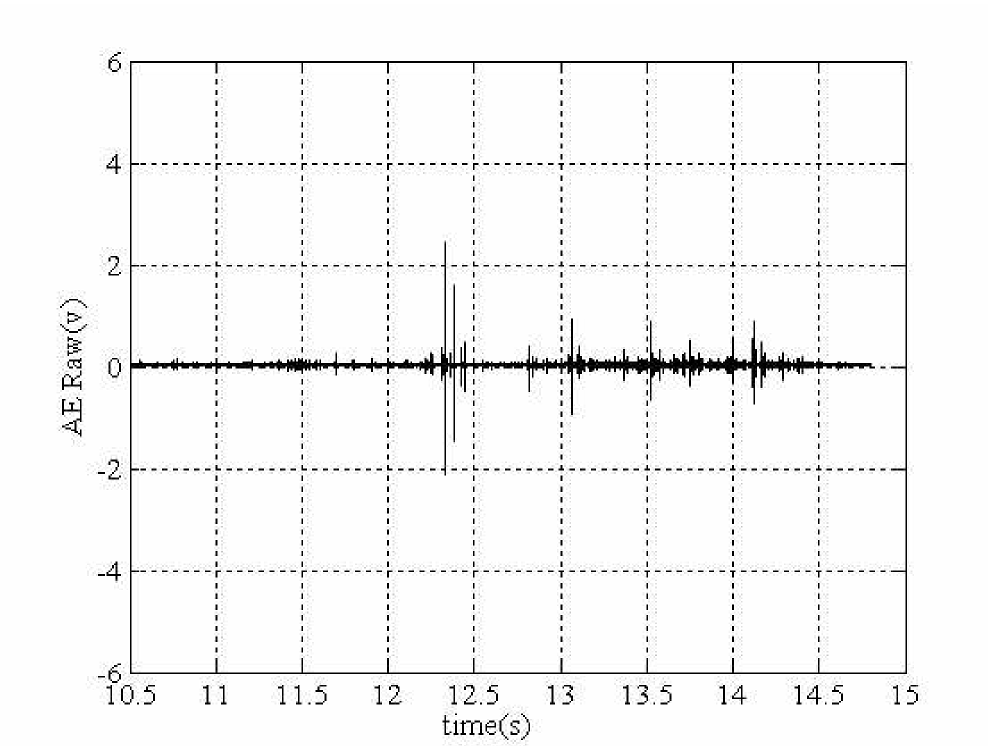


Figure 9 (d). Acoustic emission signals for scoring using cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant.
148x111mm (96 x 96 DPI)

Figure 9 (e). Effect on surface of material smearing.
76x57mm (150 x 150 DPI)

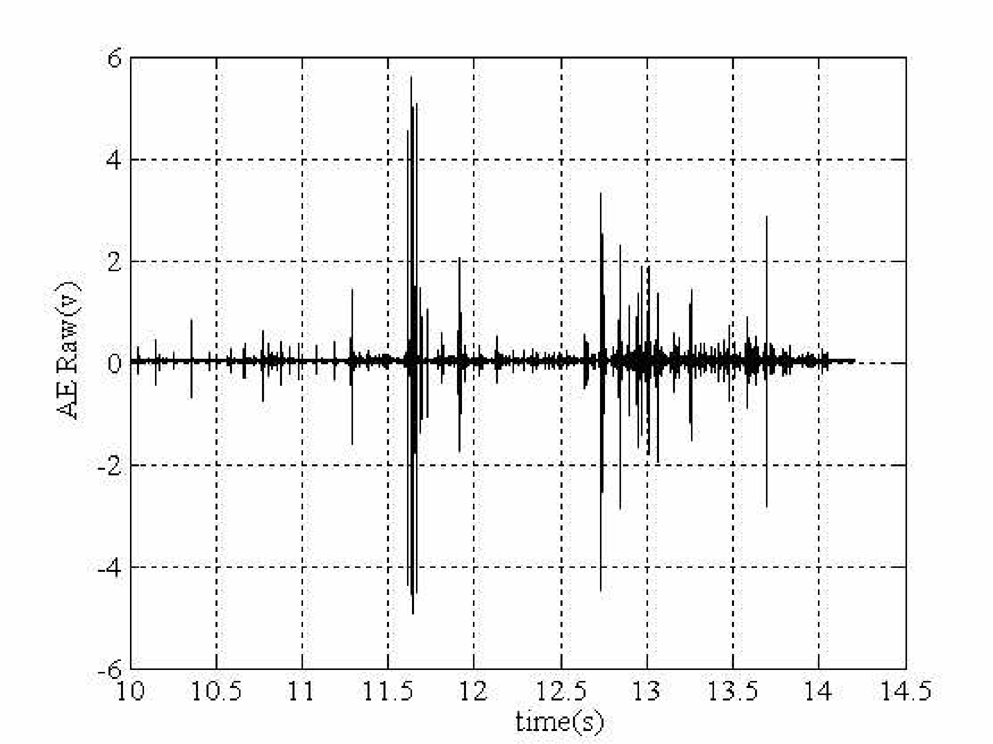


Figure 9 (f). Acoustic emission signals for smearing of segment 4 5 with blocked gullets using cutting speed of 4.75 m/min, average wear of 0.4 mm without coolant.
148x111mm (96 x 96 DPI)