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Development of process monitoring strategies in broaching of nickel–based alloys

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Abstract – Due to their stability under high mechanical and thermal loads nickel-based alloys generate high cutting forces and temperatures during machining which adversely affect tool life. Especially in broaching with form shaped tools, deviations from the original tool geometry cause an inacceptable product quality. In aero engine industry, where quality standards for machining of safety critical parts are very high, this cannot be tolerated. Because of its tool geometry broaching is different from other machining processes: due to the high ratio between cutting edge radius and chipping thickness, the influence of the tool wear at the cutting edge is strong, especially for the finishing section. In order to guarantee stable machining processes in production, monitoring methods are desired that are capable to recognize changes in cutting conditions. The EU funded ACCENT project focuses on this challenge: the goal is to use process monitoring to make conclusions about the product quality during machining and, if necessary make adjustments to process input parameters to keep the quality measures in a defined window.

Key words: ACCENT / process monitoring / nickel-based alloys / broaching

1 Introduction

Nickel-based alloys have been mostly developed to fulfill the requirements of aero engines. The face centered cubic (FCC) crystal structure of nickel is tough, ductile and stable from room temperature up to its melting point what makes them ideal for engine components subjected to high mechanical and thermal loads [1].

Failure statistics show that anomalies induced by the manufacturing process through rare events are the most common cause for a turbine disc breakdown. Given how critical these parts are and the high influence of the final machined surface, the quality of the surface being produced is a major concern for turbine manufacturers.

Due to the high surface quality produced by broaching, this process has been established as a standard process for the machining of dovetail- and fir tree slots in turbine discs. This process can be considered as a special machining operation compared to others since most of the cutting parameters are set by the tool geometry. Furthermore, given the small chip thickness along the finishing section of the turbine slots, the cutting edge radius to chip thickness ratio is relatively high. Due to this characteristic and the properties of Ni-based alloys, the tool wears relatively fast. This factor directly influences the surface quality. Therefore, process monitoring has been proposed as an approach to assist the work piece surface quality assessment in broaching. Several investigations have been conducted in order to relate process monitoring signal characteristics to surface properties [2–4]. These prove to be sensible enough to show anomalies such as chatter, scores, surface deviation and others. However, given that the tool parameters in broaching change from one tool section to the next, and even within the same tool section, it was found that the process signals have a "fingerprint" and disturbances are difficult to recognize for broaching. Therefore the implementation of a signal- or model-based monitoring system is rather difficult.

Another process monitoring approach proposed in the literature is the use of signal features. In this approach features extracted from the process signals, such as statistical values or characteristic frequencies are correlated to the desired parameter [5–7]. An advantage of feature extraction is that it reduces the data volume during the decision making step.

The objective of this study is to evaluate the use of signal features as a process monitoring strategy making qualitative conclusions regarding the achieved surface quality. For this purpose, the surface roughness and hardness of the machined surface will be evaluated as an indication

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Nomenclature

α	[°]	Clearance angle
γ	[°]	Hook angle
ρ		Pearson correlation coefficient
σ		Standard deviation
τ_{rms}	[ms]	Time constant for rms-value generation
AE_{rms}	[V]	Acoustic emission (root mean square)
AP		Amplitude
D1, D2, D3		Tool detail 1, 2, 3
DAQ		Data acquisition
f	[Hz]	Frequency
FCC		Face centered cubic lattice structure
F_x, F_y, F_z	[N]	Cutting force components in x, y, z direction
HF, LF		High frequency, low frequency
HSS		High speed steel
HV		Vickers hardness
Ni		Nickel
Ra, across		Roughness value across cutting speed direction
Ra, along		Roughness value along cutting speed direction
RPT	[μm]	Rise per tooth
SI		Surface integrity
VB	[μm]	Wear land
v_{c}	[m.min^{-1}]	Cutting speed

for its quality. The force, acceleration and acoustic emission (AE) will be investigated analyzing signal features extracted from them. The results presented in this publication intend to better understand the relation between the signal features and surface parameters.

2 Experimental set-up

A vertical broaching machine tool type Forst RISZ16$\times$1600$\times$400 at the Laboratory for Machine Tools in Aachen was used for the trials. The machine is hydraulically driven, has a maximum tractive force of 160 kN and operates at speeds up to 60 m.min^{-1} in cutting speed direction (z-axis). In Figure 1, the cutting forces are shown: the main cutting force (in cutting direction), the push-off force F_y and the axial force F_x. The dynamometer contains Kistler load cells and is specially designed for the machine tool. The natural frequency of the complete system out of machine table, dynamometer and work piece fixation is 270 Hz and was identified by impact tests in advance of the tests. Three broaching tool details (D1, D2 and D3) with different rise-per tooth (RPT) were used for the trials as shown in Figure 1. HSS tools with 12 straight cutting teeth, 4 mm width and a pitch of 10 mm were used. The land face has a clearance angle of 2°. As work piece an Inconel 718 ring of 33 mm in height and an initial outer diameter of 240 mm was used to machine the slots. In total the roughness and hardness of 45 slots were analyzed. A second work piece of the same material was used in order to perform destructive testing that is correlated and compared to the other results. Within the scope of the investigation, tests were carried out at two stages of cutting speed, 2.5 and 5 m.min^{-1}, resulting in a calculated engagement frequency of 4.2 and 8.3 Hz, respectively.

3 Roughness and hardness measurements

In the aero engine industry the term Surface Integrity (SI) has been defined as the condition of the machined surface which is given by the topography (surface) or micro-structural (sub-surface) changes. In this study, roughness, a standard SI criterion will be evaluated. Fifteen successive samples were taken for each tool detail (D1, D2 or D3). The measurement results are shown in Figure 2. The surface roughness was measured in two directions of the broached slot: in cutting direction (Ra, along) and orthogonal (Ra, across). As can be seen in Figure 2a, the Ra values are approximately in the same range for all tool details, and the RPT does not seem to have a significant influence on the machined surface roughness.

On the other hand, knowing that nickel based alloys tend to work hardening and to form a hard layer of amorphous material (white layer), the surface hardness was measured [8]. The hardness, however, represents the averaged material behavior. Therefore, it is important to keep in mind that this measurement is not capable of capturing independent SI criteria such as strain or work hardening [9]. The measured hardness is represented in Figure 2b. These values also stay in a range independent from the RPT, with the exemption of the last measurements for tool D1. This increase in the surface hardness was expected due to the condition of the tool. Other

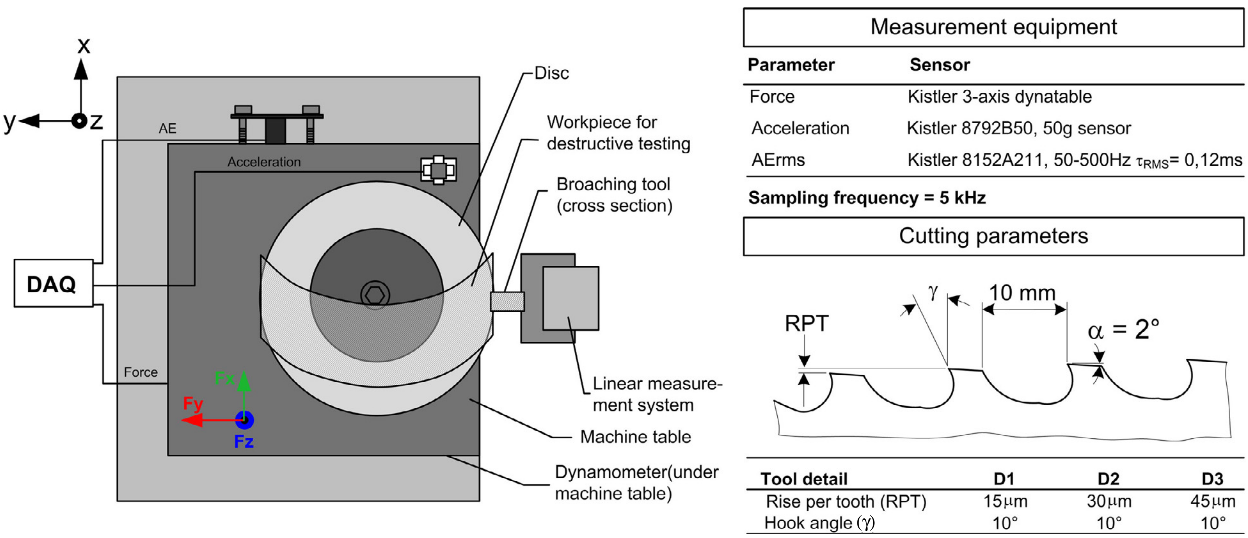

Fig. 1. Experimental set-up and DAQ (data acquisition).

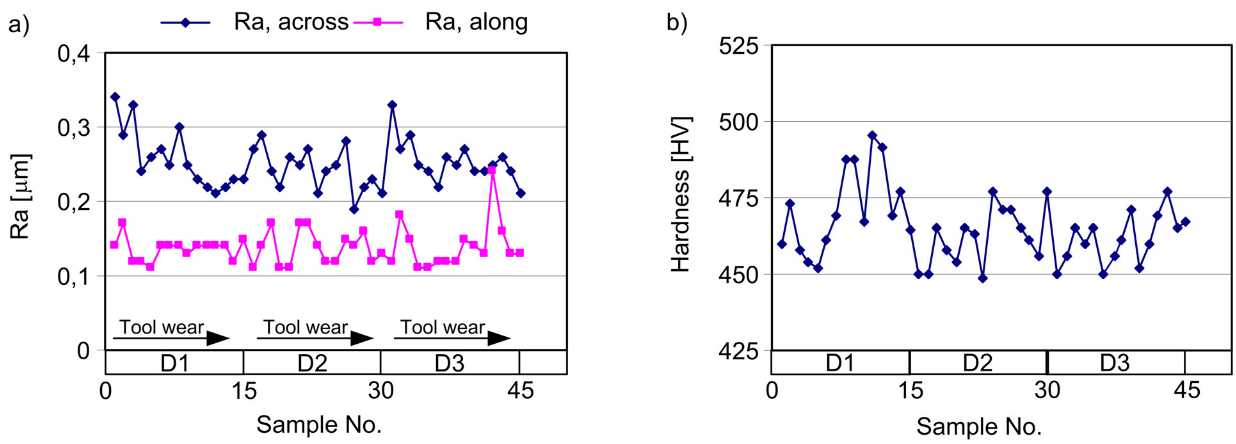

Fig. 2. (a) *Ra* value and (b) hardness of the broached surface for different tool details.

SI criteria such as residual stresses, scores and chatter will not be evaluated in this work because the intention of this work is to exemplary describe a process monitoring strategy.

4 Signal processing

Research done before in process monitoring for broaching included analysis of forces, accelerations and acoustic emission signals in order to identify characteristics that describe both, tool and surface anomalies. On this basis, several investigations were conducted in order to identify possible signal features that correlate to the surface condition in general.

4.1 Signal investigation

In the overall test series, the tool was used for 90 test slots in total which corresponds to a total cut-length of approx. 3000 mm. An overview of the tool wear is given in Figure 3 showing the tool edges (same tooth number) for the regarded tools after the last cut. For all tests, the measured wear land was biggest for the smallest RPT. The cutting edge radius for all tool edges was around 7 μm for the fresh tool. Later radius measurements, however, proved to be imprecise due to excessive smearing of work piece material.

Process forces are shown in Figure 4. The engagement and disengagement of the teeth can be recognized by an increase and decrease of the force, respectively. This rectangular distribution changes depending on process parameters such as work piece thickness, tool pitch, rise per tooth and others. In this case only the push-off force F_y is shown, but the main cutting force F_z has the same distribution. Given the effect of the cutting edge radius, F_y is relatively high compared to the main cutting force. Moreover, it has been found by other researchers [2,8], that F_y is more sensitive to changes in the process than F_z. Due to the orthogonal cutting conditions, the axial force in this case is approximately zero. As shown in Figure 4, tool

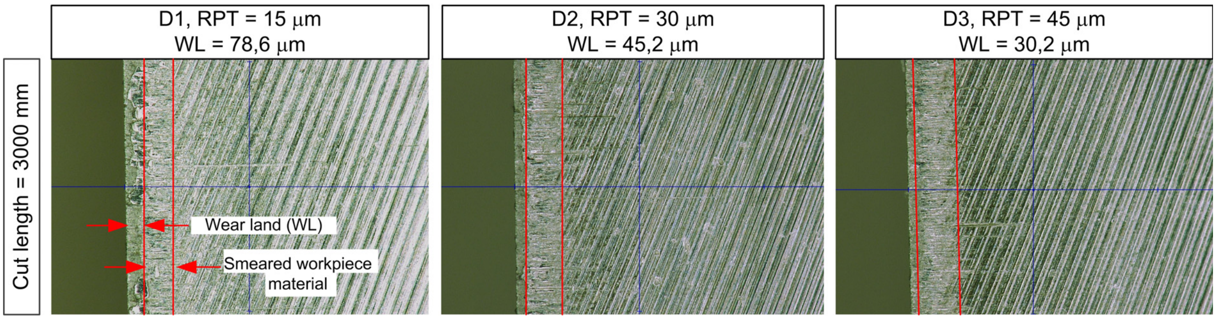

Fig. 3. Tool wear for the regarded tools at a cut length of 3000 mm.

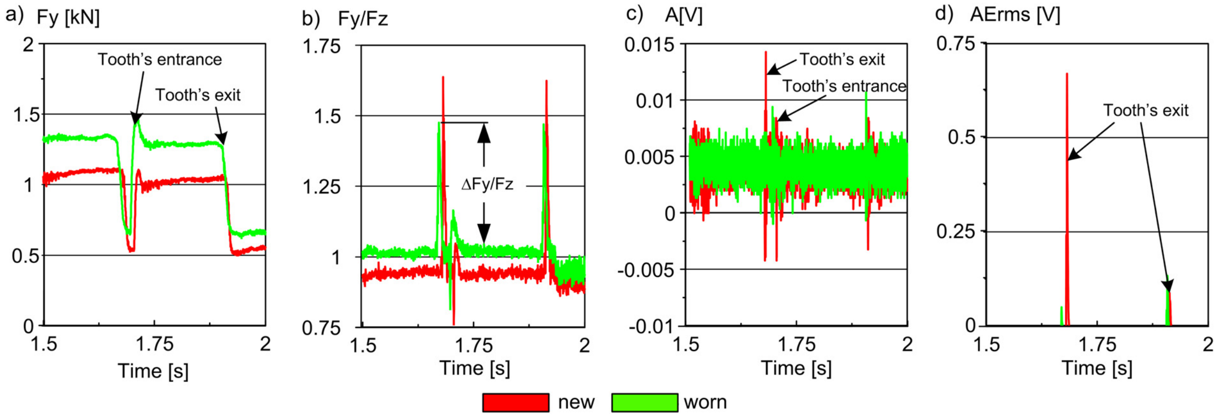

Fig. 4. Signal distributions in broaching for a new and a worn tool: (a) push-off force, (b) ratio of cutting forces, (c) acceleration and (d) acoustic emission.

wear is denoted as an increase in the force level. Since the surface deteriorates with tool wear the forces could be an indication of the changes in hardness and roughness.

Besides an independent analysis of each force component the ratio of the push-off force to the main cutting force (F_y/F_z) has also been related to surface properties. This ratio represents the impact direction of the resultant. In Figure 4, F_y/F_z for a new and a worn tool are presented. As can be seen, this ratio is almost constant between tooth entries and – exits and has peaks at their entrance and exit. In previous works [8] the amplitude of these peaks measured from the mean value were related to the surface deviation. It is also observed that this ratio increases with tool wear which means that due to wear F_y increases more rapidly than F_z.

In the acceleration signal the tooth entry and exit can also be recognized. A change in the amplitude of these peaks has also been correlated to tool condition. As shown in Figure 4, for the same cutting conditions a worn tool presents lower amplitude than a new one. This is also the case for the exit bursts seen in the AE signal (Fig. 4d). Axinte [2] found a relation between these bursts and surface and tool anomalies. Furthermore, peak amplitude in the force and acceleration spectrum can be used to identify process malfunctions [3]. In Figure 5, the force and acceleration spectrum for specific frequency bands are shown. The low frequency band (0–50 Hz) of the force spectrum shows the highest peak at the engagement frequency and its harmonics. The amplitude of this peak is related to the static component of the cutting forces.

Additionally, pre-machining tests were conducted in order to find the system's characteristic frequency. This is located around 270 Hz. The force and acceleration signal in frequency domain from 200 to 500 Hz are shown in Figures 5b and c, respectively. A peak at the characteristic frequency can be seen in these spectrums. An additional peak at around 325 Hz was also found. Axinte [2] found, such peaks in the acceleration and force spectrum were related to different tool conditions that affect the surface.

4.2 Feature extraction

In the previous section the basic signal characteristics of the force, acceleration and AE_{rms} in time and frequency domain were investigated. The next step is to extract features from the signals that could be related to the surface condition and therefore describe the roughness or hardness. As proposed in a publication by Sokolowski [6], basic time domain based parameters, such as maximum, minimum, mean and other statistical values have been extracted for the cutting forces, F_y/F_z ratio and AE as possible features. Also from the frequency domain of the the cutting forces, F_y/F_z ratio and acceleration the amplitude for characteristic peaks was obtained. Table 1 contains the list of the features extracted from the signals. In order to not neglect the effect of the progressing tool

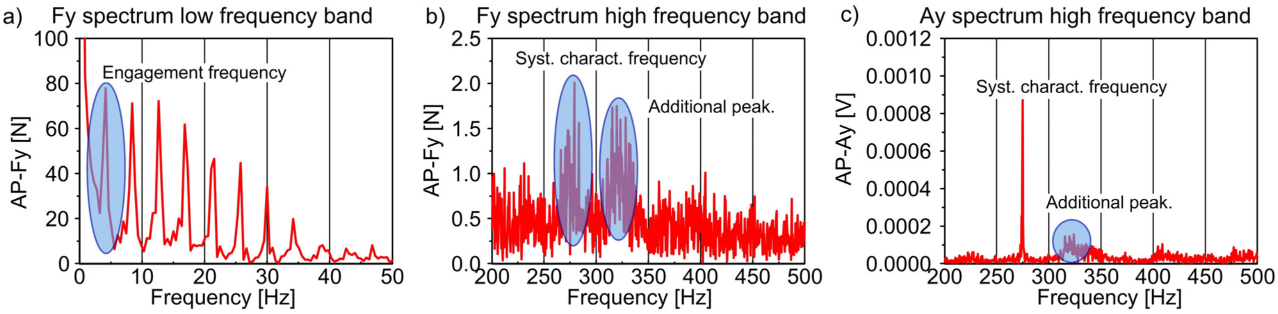

Fig. 5. Force and acceleration spectrums.

wear, the signal features were calculated from every 5th cut from all 90 cuts being made in total.

The first six features correspond to statistical values regarding the relation of the push-off force to the main cutting force (F_y/F_z). Given that this value stays relatively constant during the cutting process, several values that indicate a deviation from the mean have been extracted. In the time domain the force signals in y- and z-direction are highly sensitive to the process. In broaching due to the entry and exit from each tooth the force signal steps up and down. Given the changing force magnitude, only the mean force value has been considered as an indication of the average force level during the cutting process. This value reflects the cutting conditions and therefore it is assumed to strongly correlate to SI parameters.

In the frequency domain, the amplitude of the highest peak in two frequency bands was analyzed to verify if this amplitude reflects a process anomaly. It is proposed that in the high frequency range, the amplitude of the maximal peak is an indication of vibrations deteriorating the surface. Besides that, in the low frequency band, the amplitude of the peak represents the average force level. From the AE_{rms} signal in time domain several statistical values which indicate the presence of bursts are extracted to determine their potential to describe the surface.

4.3 Feature selection

For the feature selection Pearson correlation coefficient as suggested by Scheffer [7] is used. This coefficient establishes which features present a linear relationship with the roughness and hardness. This coefficient is calculated using the following equation:

$$\rho_{x,y} = \frac{Cov(X,Y)}{\sigma_x \cdot \sigma_y} \tag{1}$$

where $\rho_{x,y}$ is the Pearson correlation coefficient and σ the standard deviation for x and y. The variables x and y are the signal features and surface parameters, respectively. The covariance from the variables is calculated with Equation (2).

$$Cov(X,Y) = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y}) \tag{2}$$

the coefficient ρ is inside the interval [–1,1] and is: –1 if one variable has an inverse relation to the other, 0 if the variables are completely independent or 1 if one variable has a direct relation to the other. The Pearson correlation coefficient of the signal features was calculated for 45 samples.

5 Results and discussion

The Pearson correlation coefficient was calculated between the signal features and the surface characteristics. The results are presented in Figure 6a in absolute value and per cent. As can be seen, none of the signal features presents a high correlation to either of the surface parameters.

The feature, which corresponds to the arithmetic mean value of the push-off, and the roughness across the cutting speed a correlation of –0.55 was found. That means that a moderate negative linear correlation exists between both variables, however, does not necessarily mean that the Ra value is caused by this force. Nevertheless, as stated by Scheffer [7], there should be a reasonable physical explanation for the behavior of a feature with respect to the objective.

In order to better understand the physical relationship, the mean values of F_y and F_z mean values are normalized and represented together with Ra, across for the 45 samples in Figure 6b. The tendency for each tool detail has been drawn. It can be seen that as Ra decreases, the forces increase with tool wear. For F_z, however, there is also a considerable rise with increasing RPT. According to this, it can be implied that the roughness across the cutting speed is dependent on the tool wear, but independent from the RPT. A sharp tool has a small cutting edge radius and the land face is not in contact with the work piece due to the clearance angle. With progressing tool wear, the edge radius increases and the clearance at the wear land is reduced. Hence, the contact area between tool and the cut surface becomes bigger. As a consequence of these phenomena, the cutting force increases due to a larger edge radius and the push-off force rises on account of the increased contact area at the tool work piece interface. The bigger contact area contributes to a flattening or "ironing effect" where the surface topography generated by the cutting process is smoothed by the overrunning

Table 1. Description of features.

	Feature No.	Feature	Signal	Description
Time domain	1	F_y/F_z min	F_y/F_z	Minimal value
	2	F_y/F_z max	F_y/F_z	Maximal value
	3	F_y/F_z arith mean	F_y/F_z	Arithmetic mean value
	4	F_y/F_z stand dev	F_y/F_z	Standard deviation
	5	F_y/F_z variance	F_y/F_z	Variance
	6	F_y/F_z avg abs dev	F_y/F_z	Average absolute deviation
	7	F_y mean	F_y	Arithmetic mean value
	8	F_z mean	F_z	Arithmetic mean value
Frequency domain	9	$AP{-}F_y$ (HF)	F_y	Ampl. highest peak between 200–500 Hz
	10	$AP{-}F_z$ (HF)	F_z	Ampl. highest peak between 200–500 Hz
	11	$AP{-}F_y/F_z$ (HF)	F_y	Ampl. highest peak between 200–500 Hz
	12	$AP{-}A_y$ (HF)	A_y	Ampl. highest peak between 200–500 Hz
	13	$AP{-}A_z$ (HF)	Az	Ampl. highest peak between 200–500 Hz
	14	$AP{-}F_y$ (LF)	F_y	Ampl. highest peak between 1–50 Hz
	15	$AP{-}F_z$ (LF)	F_z	Ampl. highest peak between 1–50 Hz
Time domain	16	AE_{rms} max	AE_{rms}	Maximal value
	17	AE_{rms} arith mean	AE_{rms}	Arithmetic mean value
	18	AE_{rms} sq. mean	AE_{rms}	Square mean value
	19	AE_{rms} stand dev	AE_{rms}	Standard deviation value
	20	AE_{rms} variance	AE_{rms}	Variance

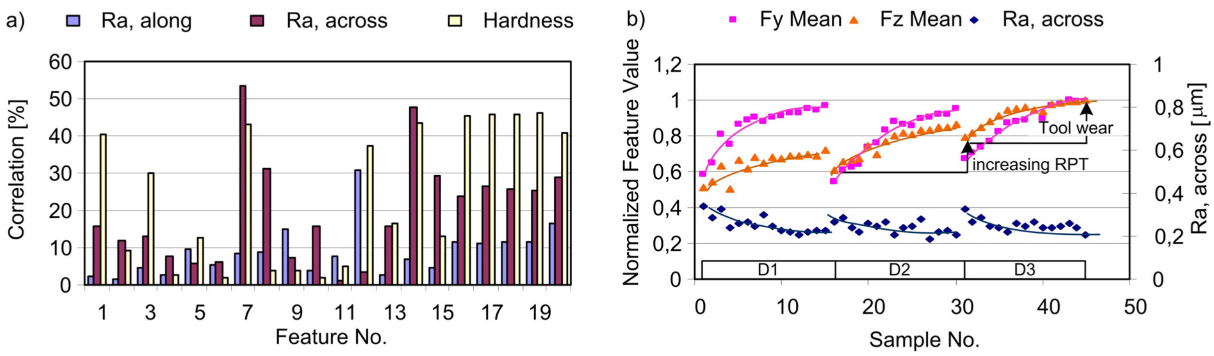

Fig. 6. (a) Correlation factors and (b) relation between features and Ra, across.

tool, which results in a lower roughness value. Besides that the build-up edges, which affect the roughness across the slot and are very common for Ni-alloys, occur in the contact zone. From this example, it can be seen that even though an increase in F_z relates to the changes on the surface, the changes due to different cutting RPT are more significant.

The hardness shows a weak relationship to several of the signal features. Considering that the low correlation could be due to the different cutting parameters, the coefficient was recalculated for each detail independently. For tool detail D3 it was found a correlation of 0.64 with AE_{rms} arithmetic and 0.55 with the highest peak in the low frequency band from the push-off force. That means the hardness and the feature present a moderate negative and positive linear relationship, respectively.

In Figure 7a, the hardness is plotted in relation to the normalized features. The relation between a decrease in the acoustic emission mean and an increase in the push-off force for increasing hardness is probably due to the microstructural changes. A Ni-based alloy tends to work hardening and white layer formation. The surface hardness represents the averaged material behavior of these two factors. From metallographic analysis, it was found that with increasing tool wear both, the white and the distorted layer become thicker. This is awaited as an increasing push-off force component has a stronger ironing effect. Furthermore, in other investigations it was found that a thicker white layer produces a decrease in AE_{rms}.

The surface roughness Ra along the slot showed a weak linear correlation to Feature 12, which corresponds to the highest peak amplitude from the high frequency of the acceleration spectrum. As stated before, peaks in the high frequency band represent process anomalies that in this case affect the roughness in cutting direction. However, given the low correlation between these feature and Ra, along other features to describe the surface roughness in this direction are required.

6 Conclusion

It was found that most features do not display any trend with the roughness and hardness. It is clear from the

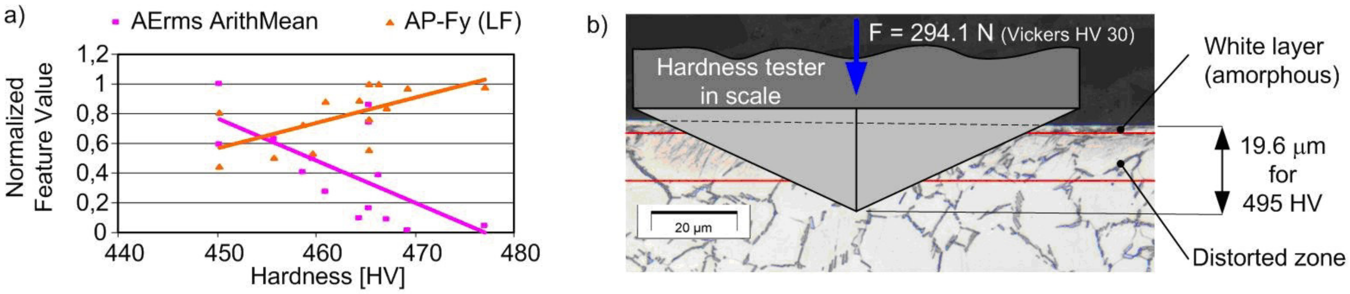

Fig. 7. (a) Linear relation between surface hardness and features, (b) microstructural changes perceived by Vickers HV 30 hardness measurement.

results that although the features have a tendency to be linearly related to the surface parameters, there is a large degree of variance present and the correlation with the actual surface condition will be rather poor. That could be due to the fact that data from the shop floor is extremely noisy. It is also important to consider that due to different cutting conditions in many cases the changes produced in the signal features are bigger than the changes related to the factors affecting the surface quality. Therefore, the correlation of signal features to the surface characteristics should be done independently for different cutting conditions. It can be concluded that the use of features as a means to determine SI has a high potential, however, several features that work only for specific cutting conditions have to be evaluated at the same time in order to make the final statement of only one SI parameter. The combination of these statements could then give an estimation of the surface quality.

The benefit of an implemented monitoring tool for industry is obvious: being able to predict the actual tool condition during machining or – even further – different surface integrity parameters, decisions such as making tool changes without running out of quality tolerances could be supported. Consequently, tooling costs could be reduced, which especially in case of broaching where expensive, non-standardized tools are employed is of large interest.

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