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Mathematical Pattern Recognition Techniques Applied to Wear Debris Characterisation for Condition Monitoring of Gas Turbine Engines

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Abstract

The automation of wear debris characterisation by SEM / EDX analysis using mathematical pattern recognition techniques offers a reliable identification of particle alloy composition. It is less time consuming than an individual check for the best fitting material. Another advantage is the full automatic generated Word report, which can be easily distributed by LAN or email.

Introduction

A standard tool for condition monitoring and early failure detection of jet engines and other tribological systems are magnetic plugs in combination with the characterisation of the collected wear debris by SEM / EDX analysis. The quantitative analysis of the elemental composition of individual wear particles is used to indicate and localise a damage in its early stages and in general before a critical phase occurs.

In our institute about 3700 jet engines and other tribological systems of 86 different types are under early failure detection control. About 50% of the units are equipped with magnetic plugs. The percentage increases steadily and so does the number of wear particles to identify. Additionally depending on the system up to 30 different relevant alloys are used of which wear particles are found in the debris.

Due to the importance for operational safety of jet engines and other tribological systems wear debris analysis is used for years and was described in several articles. To optimise the identification process and to reduce the time and manpower effort, different attempts for automation were taken in the past. In most cases automation focuses on sample handling and on an automatic (mostly unattended) scanning of the debris sample with subsequent alloy identification and statistical interpretation. Particle analysis is in general done by x-ray fluorescence or SEM/EDX analysis with the sample mounted on a xy-scanning stage.

It is unquestioned that the quality of the analytical data about particle composition is directly related to an unambiguous alloy identification. But alloy identification is made complicated because debris samples removed from magnetic plugs in most cases are present as agglomerates of particles of different origin. So unattended analysis in general does not separate contaminant particles sticking to the debris particle of interest. The result is an increasing number of unidentified or questionable alloys. Moreover, due to alloy inhomogenity small spot analysis has to be avoided for particle identification. For improved results spot size has to be optimised to particle size, while excluding attached agglomerates. Additionally particle geometry and orientation is of influence on the analytical results. Excluding simple cases, from our experience debris analysis has to be done by an operator guided analysis. But automation is possible and very effective by using mathematical pattern recognition techniques to reduce the boring and time consuming alloy identification process. Unrenounceable requirement is the quality of the analytical data.

It is expected, that wear debris characterisation by SEM/EDX will continue to be of high importance in the future and for modern tribological systems equipped with chip detectors. Chip detectors only reduce the number of inspections and the determination of the amount of debris. In the case of excessive debris production debris analysis and alloy identification is still of interest.

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As an example, the need for a reliable alloy identification can also be made clear by the number of samples to identify in the case of the RB 199 engine. The Bundeswehr operates about 800 RB 199 jet engines. Each engine is equipped with 5 or 6 magnetic plugs. On the average, each engine is operated 150 hours per year. Magnetic plugs are inspected after 19 hours of operation. This results to 32000 inspections per year. Only in about 100 cases (0.3%) excessive wear is found and send in for debris analysis. In 20% of these 100 questionable cases the engines could be directly operated again, because normal debris due to run in period or uncritical foreign matter sources was detected. In 55 cases (0.15%) a recommendation for oil change an test operation was given. Only in 25 cases (0.07%) the change of an engine was recommended. Taking into account the costs for recommended service, the need for reliable and precise debris identification becomes clear. Widely automated systems tend to fail this goal.

So having both capabilities (automated scanning and operator controlled analysis) we favour the second way while optimising the identification process by mathematical pattern recognition techniques because better results are obtained. Identification can be done by principal component analysis (PCA) or hierarchical cluster analysis (HCA) applied to quantitative EDX results on a routine basis. We use a modified HCA technique.

A data set of reference alloys, depending on the tribological system, is automatically extended by the composition of wear particles analysed. The mathematical pattern recognition techniques aid the analyst to see clustering of the multivariate data in higher dimensional spaces. Instead of a time consuming comparison of scattering quantitative results for individual elements of the alloys, the pattern recognition procedure determines the similarity of a complete data set with reference data. It looks for a similarity in element composition and not for individual element concentrations. Thus scattering of the quantitative results for individual element concentrations, which can not be ruled out in SEM/EDX analysis of microscopic particles, is less critical. The techniques can be implemented in an expert system which makes the identification of wear particle alloys less time consuming and which helps to reduce the misinterpretation of the data. Though the whole diagnostic routine is very reliable, fast and cost-saving, it may be improved. Depending on the system, up to 30 different relevant alloys are used of which wear particles are found in the debris.

EDX-Analysis

With scanning electron microscopy (SEM), combined with energy dispersive x-ray analysis (EDX), the interesting particles are analysed. Typically, 14 elements (V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, Ag, Cd, W, Al, Si) are quantified. Depending on the tribological system, additional elements can be taken into account if required. The accuracy of the EDX-analysis is shown in fig. 1:

After all particles are analysed, the data sets are transferred from the EDX-computer (PDP 11) to a expert system based on a PC via the serial interfaces and stored in a text file.

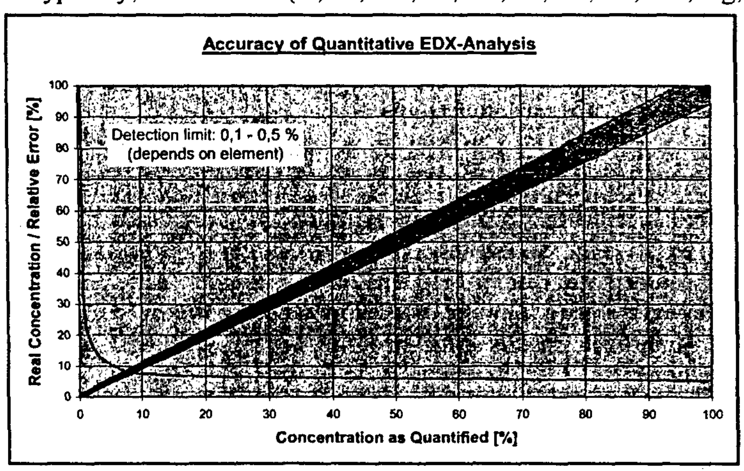


Fig. 1 Accuracy of EDX-analysis

Data Base

As shown in fig. 2, the user has to select a certain tribological system. Implemented are the RB 199 and APU engine of the Tornado, the Tornado gearbox and the engines of three different helicopters (UH-1 D, BO 105 and Sea King). The RB 199 and the Sea King engine data sets are divided in 5 (see fig. 3) respectively 3 magnetic plugs.

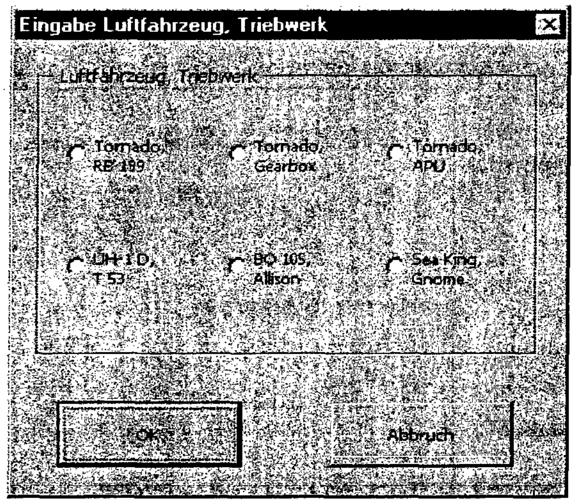


Fig. 2: The Tornado and 3 different helicopters are checked by SEM / EDX analysis

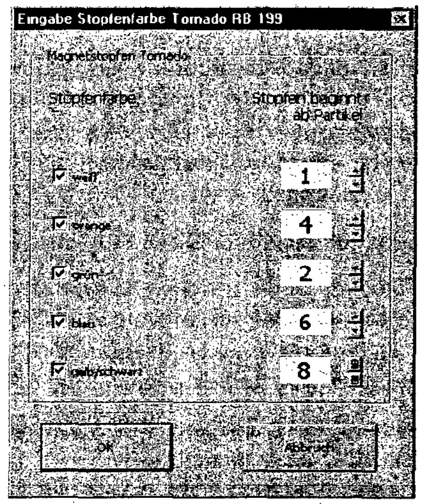


Fig. 3: The RB 199 consists of 5 different tribological systems, monitored by magnetic plugs

Each tribological system contains specific alloys and related parts. This information is stored in Excel worksheets, which can be changed or supplemented without problems (fig. 4).

Magnetstopfen.xls

	A	B	C
1	Triebwerk	Bauteil, Komponente	Werkstoff
2	RB 199, weiß	Lager 1 + 2: Innenring	MV 1172
3	RB 199, weiß	Lager 1 + 2: Außenring, Wälzkörper	MV 1174
4	RB 199, weiß	Rollenlager 1 + 2: Käfig	100Cr6
5	RB 199, weiß	vord. Lagerkammer: Labyrinthdichtung S3, Öldichtring, IPC S7	MV 1211
6	RB 199, weiß	Gehäuse: Dichtgehäuse, Dichtungsgehäuse	MV 1211
7	RB 199, weiß	Beschichtungen, Leitschaufelgehäuse St 3: Verschleißschicht	MSRR 9507/1
8	RB 199, weiß	Beschichtungen, Dichtungsgehäuse: Einlaufbelag	MSRR 9507/5
9	RB 199, weiß	Beschichtungen, Dichtungsgehäuse: Einlaufbelag	MSRR 9507/6
10	RB 199, weiß	Ag-Beschichtung	Ag-Beschichtung
11	RB 199, weiß	Cu-Beschichtung	Cu-Beschichtung
12	RB 199, weiß	Zn-Beschichtung	Zn-Beschichtung
13	RB 199, weiß	Ni-Beschichtung	Ni-Beschichtung
14	RB 199, weiß	Al-Beschichtung	Al-Beschichtung
15	RB 199, blau	Lager 3: Innenring, Außenring, Wälzkörper	MV 1174
16	RB 199, blau	Lager 3: Käfig	100Cr6
17	RB 199, blau	Lager 4: Innenring, Wälzkörper	MV 1174
18	RB 199, blau	Lager 4: Außenring	MV 1172
19	RB 199, blau	Lager 4: Käfig	100Cr6
20	RB 199, blau	Lager 4a: Innenring, Außenring, Wälzkörper	MV 1174
21	RB 199, blau	Lager 4a: Käfig	100Cr6

Tornado / UH-1D / Sea King / BO 105 / Werkstoffe / EDX Konz / W. Konz / Ergebnis / Bauteile / Fiktive Bauteiltabelle / Fehler

Fig. 4: Part of Tornado's component table. For each part, the alloy name is given.

In another Excel worksheet, the composition of all alloys is summarised (see fig. 5).

Magnetstopfen xls

Element	Fe		Cr		Mo		V		Ni		W		Mn		Al		Si		Co		Ag		Cd		Cu		Zn	
Werkstoff	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
1.3502																												
1.4911																												
1.5924																												
1.5934																												
1.6604																												
1.6722																												
1.6723																												
100Cr6																												

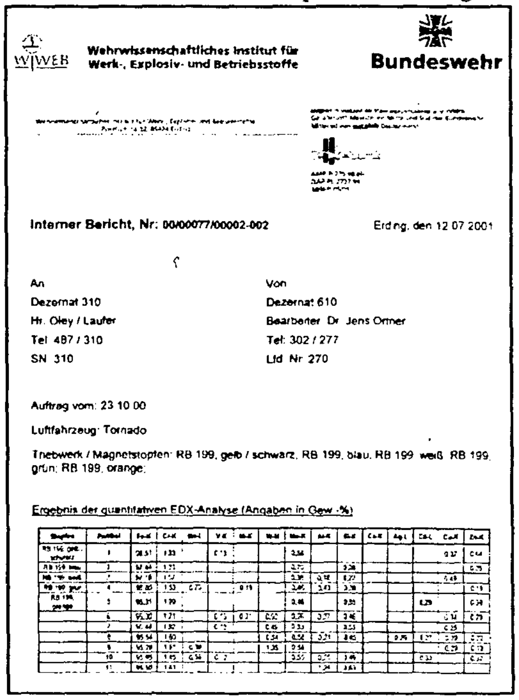
Fig. 5: The composition of all materials involved in the above mentioned tribological systems.

Visual Basic Program

The EDX-data of the debris wear particles are compared with the materials of the specific tribological system. With a pattern recognition algorithm the best fitting material is selected and all components, made out of this alloy are determined. Finally an automatic report is generated.

The program consists of the following procedures:

1) Selection of the tribological system (see fig. 2). To section the data set for Tornado RB 199 and Sea King Gnome engines, the number of the analysed particles have to be assigned to the plugs (fig. 3).
2) Generation of an Excel worksheet with the data of the EDX-analysis text file.
3) Depending on the tribological system, the software selects a reference data base including parts and alloys.


WIWEB Wehrwissenschaftliches Institut für Werk-, Explosiv- und Betriebsstoffe

Bundeswehr

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Erding, den 12 07 2001

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Lfd Nr 270

Auftrag vom: 23 10 00

Luftfahrzeug: Tornado

Triebwerk / Magnetstopfen: RB 199, gelb / schwarz; RB 199, blau; RB 199 weiß; RB 199, grün; RB 199, orange;

Ergebnis der quantitativen EDX-Analyse (Angaben in Gew.-%)

Fig. 6: First page of the Word report with the data of the EDX-analysis.

4) Pattern recognition algorithm:
   a) Determination of the optimised reference concentration for alloys where a concentration range is defined instead of a single value. In this case the best fitting value has to be determined.
   b) For each particle, the similarity value relative to possible alloys is calculated. The similarity is determined by the differences in the elemental concentrations between a particle and all possible materials. To improve selectivity the pattern recognition algorithm is optimised for specific elements and concentration ranges. This is necessary because the element concentrations significant for the identification range between 1% and 20 %. This may be explained by the following examples:
      - If the difference is calculated by formula 1 (absolute error), the main element is dominant and wrong materials are identified.
      - If the difference is calculated by formula 2 (relative error), the elements with very low concentrations (< 1%) get dominant.

$$D=\sqrt{\sum_{i=1}^{E}(P_i-M_i)^2} \quad (1); \qquad D=\sqrt{\sum_{i=1}^{E}\left(\frac{P_i-M_i}{M_i}\right)^2} \quad (2)$$

$D = Difference$

$E = Number\ of\ elements$

$P_i = Concentration\ of\ element\ i\ in\ the\ particle$

$M_i = Concentration\ of\ element\ i\ in\ a\ material$

   If a coating is present, the particle has to be identified as a coating. Therefor a different algorithm has to be used for particles with significant concentration of Ag, Cd, Cu, Zn, Ni or Al.

   c) Determination of the best fitting alloy for each particle. If more materials are similar, they all have to be listed including a ranking.

5) For all alloys identified, the relating parts are determined.

6) Generation of a Word report (see fig. 6 - 7).
7) Data exchange by the institute's LAN.

Results

Particle	Material (best fit)	Similarity	Alternative Materials	Similarity
1	MV 1175	69.63%	-	
2	MV 1175	75.81%	-	
3	MV 1175	73.36%	-	
4	MV 1175	76.04%	-	
5	MV 1175	73.71%	-	
6	MV 1175	68.82%	-	
7	MV 1175	62.56%	MV 1137	58.72%
8	MV 1171	56.71%	MV 1175	53.15%
9	MV 1175	82.84%	-	
10	MV 1175	66.40%	-	
11	MV 1175	71.41%	-	
12	Ni-coating	52.59%	-	
13	Ni-coating	42.44%	-	

Parts

Plug	Material	Parts
RB 199, gelb / schwarz	MV 1171	Außengetriebe: Wälzlager, Innenring;
	MV 1175	Außengetriebe: Wälzlager, Wälzkörper; Doppelschulterkugellager: Wälzkörper;
	MV 1137	Getriebe: Welle Innengetriebe, Verzahnung;
	Ni-coating	Ni-Beschichtung;

Comments

***Fig. 7:** Last page of the Word report with the results of mathematical pattern recognition.*

Summary:

The automation of wear debris characterisation by SEM / EDX analyses using mathematical pattern recognition offers a reproducible and reliable technique and is less time consuming than an individual check for the best fitting material. Another advantage is the full automatic generated Word report, which can be easily distributed by LAN or email.