A Computerised Wear Particle Atlas for Ferrogram and Filtergram Analyses

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Abstract: A new computerised wear particle atlas has been developed for identification of solid particles and differentiation of wear severity of lubricated equipment. This atlas contains 892 images of representative solid particles selected from thousands of filtergram and ferrogram slides, enabling to cover diverse ferrous, nonferrous and contaminant particles in used lubricants. The unique wear severity differentiation atlas, which combines measurable particle parameters with comparable particle images, significantly benefits standard wear particle analysis.

key Words: Condition Monitoring; ferrogram; filtergram; particle images; wear particle; wear particle atlas; wear severity level.

1. Introduction: A wear particle atlas is probably the most valuable reference for microscopic wear particle analysis. The first wear particle atlas, which was developed in 1976 [1] and revised in 1983 [2], has significantly contributed to application and development of wear particle analysis in machine condition monitoring. However, as this atlas mainly focuses on identification of the solid particles separated by ferrogram method (i.e., Analytical Ferrograph), its role in guiding wear condition monitoring is restricted. To develop a new wear particle atlas is thus increasingly indispensable based on the following considerations:

- Recently, various non-magnetic particle separation methods, such as the filtergram method (using cellulous filter membrane) developed by Monash University [3] and the filter-based back-flush method from the pore-blockage particle counter sensor [4], etc, have been used to strengthen wear particle analysis. Because the visible features of solid particles between the two separation methods, such as position, orientation and sizing etc, are often dissimilar due to different particle separation principles, the identification guidelines for ferrogram particles are not appropriate to filter-based methods (in general, filtergram method).

- Microscopic wear particle analysis is still a qualitative and non-standard operation. In particular, differentiation of machine wear severity levels based on wear particle analysis is currently an entirely person-dependant activity [5]. It is not unusual that different analysts could make inconsistent judgements on the wear severity level of same oil sample, resulting in high risk factor in machine condition monitoring and difficulty in data/information communication. Though it is far from establishing a quantitative standard for wear severity differentiation using automated image analysis technology, a well-developed wear particle atlas seems to be still able to improve consistency of wear particle analysis significantly. To develop a wear severity differentiation atlas, which combines measurable and important particle parameters with visible and comparable particle images to illustrate sequential wear processes, will be a cost effective alternative.

- Application of various software packages in oil & wear debris analysis and lubrication maintenance has demanded a computerised wear particle atlas for more efficient image comparison and correlation analysis. Remarkable development in PC and data storage technologies has also enabled thousands of colour images to be recorded on a CD disk with low cost.

Based on the expertise in both ferrogram and filtergram wear particle analyses during the past decades, ***Lubrosoft*** has developed a computerised wear particle atlas (called Wear Particle Atlas 97) to meet the advanced requirements above.

2. Hierarchy: Wear Particle Atlas 97 covers three main categories of solid particles in lubricants, i.e., Contaminant Particles, Nonferrous Wear Particles and Ferrous Wear Particles. The hierarchy of the atlas is shown in Table 1-3.

Table 1 Contaminant Particles

1.1 Contaminants	1.2 Contamination Level
1.1.1 Silica Dusts - Filtergram & Ferrogram	Level 1
1.1.2 Carbon Dusts - Filtergram & Ferrogram	......
1.1.3 Ferrous Oxides - Filtergram & Ferrogram	Level 10
1.1.4 Fibre - Filtergram only	
1.1.5 Soft Compounds - Filtergram & Ferrogram	
1.1.6 Corrosive Particles - Ferrogram only	

Table 2 Nonferrous Wear Particles

2.1 Materials	2.2 Wear Modes	2.3 Wear Severity
2.1.1 Copper Alloy	2.2.1 Rubbing Wear	Level 1
2.1.2 Aluminium Alloy	2.2.2 Cutting Wear	....
2.1.3 Lead/Tin Alloy	2.2.3 Fatigue Wear	
	2.2.4 Sliding Wear	Level 10

Table 3 Ferrous Wear Particle

3.1 Materials	3.2 Particle Modes	3.3 Wear-Mode-Related Severity
3.1.1 Cast Iron	3.2.1 Rubbing Wear	3.3.1 Rubbing Wear Severity
3.1.2 Low Alloy Steel	3.2.2 Cutting Wear	3.3.2 Cutting Wear Severity
3.1.3 High Alloy Steel	3.2.3 Fatigue Wear	3.3.3 Fatigue Wear Severity
	3.3.4 Sliding Wear	3.3.4 Sliding Wear Severity
	3.3.5 Combined Sliding and Fatigue Wear	3.3.5 Combined Wear Severity

A total of 8 sub-categories, which contains 892 representative colour particle images, cover a wide range of wear conditions of lubricated equipment. A total of 14 graphic interfaces are employed to guide particle identification and search more efficiently. While opening the atlas, Home Page (Fig 1) will appear firstly, in which 8 wear particle images are representative of 8 sub-categories of solid particles respectively. Through clicking each image, the correspondent sub-category pages, which also contain representative particle images to represent each sub-sub-category, will occur. For instance, clicking the image labelled as "Nonferrous Materials" from Home Page, the Nonferrous Material sub-page, which contains 3 typical nonferrous metal particle images of representing Copper, Aluminium and Lead/Tin alloys respectively, will appear (Fig 2). Further clicking the image labelled as Copper-Ferrogram, the working page (Fig 3) will appear to show the various images of the copper metal wear particles separated by ferrogram method.

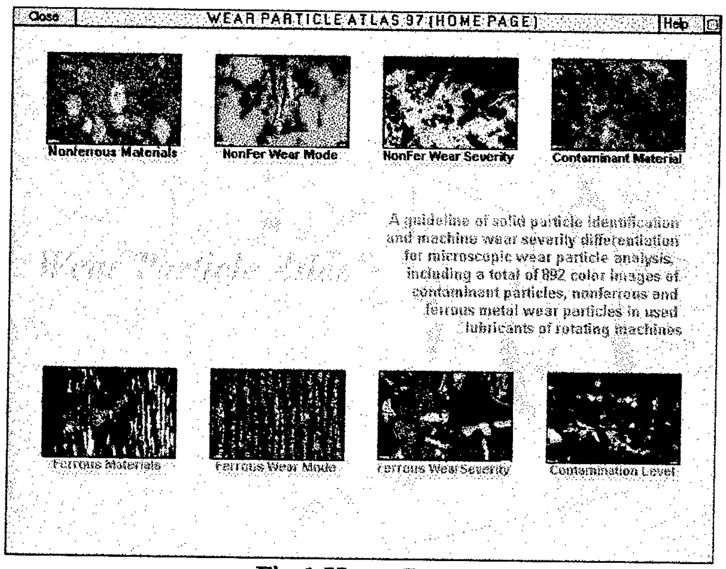

Fig 1 Home Page

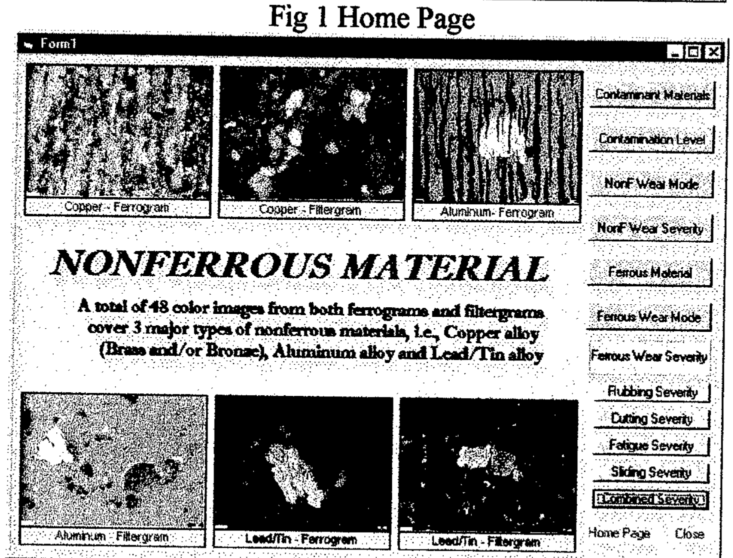

Fig 2 Sub-category - Nonferrous Materials

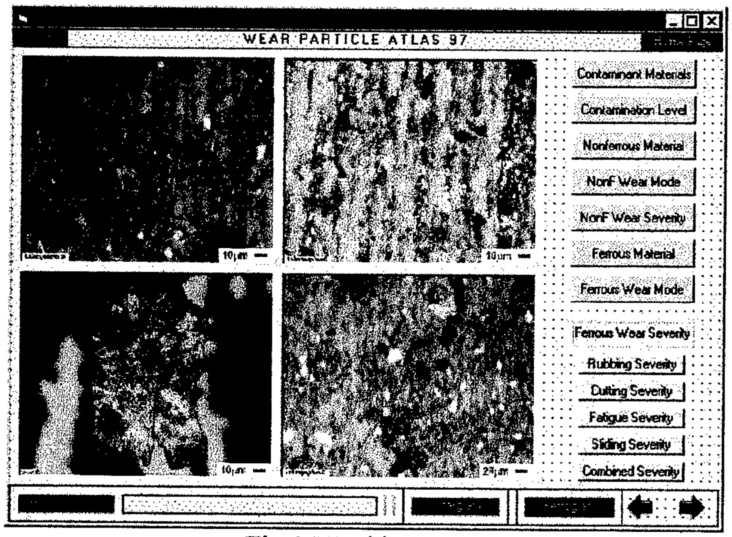

Fig 3 Working page

3. Characteristics

3.1 Complementary Integration of Two Particle Separation Methods: The ferrogram method is excellent in identifying materials of solid particles but deficient in collecting nonferrous particles, whereas the filtergram method is prominent in collecting all solid particles larger than the pore size of the filter membrane but restricted in identifying materials of solid particles. Wear Particle Atlas 97 exclusively embraces the solid particles from both filtergram and ferrogram methods, enabling to compensate their respective limitations to maximise the strengths of microscopic wear particle analysis.

Fig 4 (a) shows an easy-to-identify nonferrous wear particle image on a ferrogram slide. The non-magnetic deposition pattern of the white metal particles on this ferrogram slide makes them to be discriminated from the ferrous particles easily. As colour and brightness of both ferrous and white metal particles are very similar and lack of depositing orientation and locations as on a ferrogram, it is very difficult to identify these nonferrous particles from the ferrous particles while they are on the filtergram slide, see Fig 4 (b).

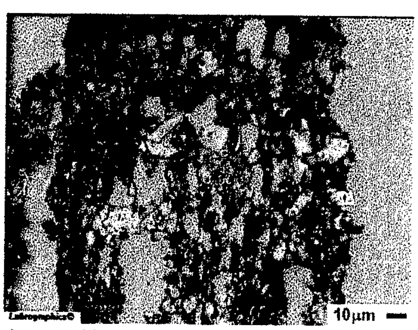

Fig 4 (a) Lead/Ton particles on a ferrogram

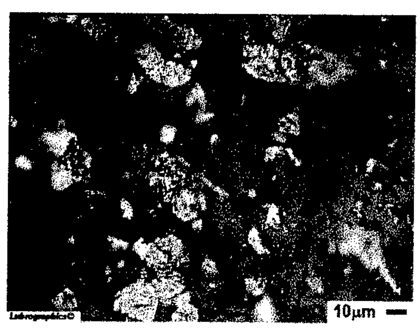

Fig 4 (b) Lead/Tin particles on a filtergram

On the other hand, however, the filtergram method can collect nonferrous metal particles with high efficiency, showing a high reliability in detecting wear condition of nonferrous components. Fig 5 (a) shows the massive rubbing copper wear particles on a filtergram slide from a worm gearbox, revealing a high wear rate of the copper worm gear. But the ferrogram, which is made of same volume of oil sample, shows a very low copper particle concentration, see Fig 5 (b). It is estimated that the collecting efficiency of ferrogram method for small copper particles is likely to be less than 10% in this case.

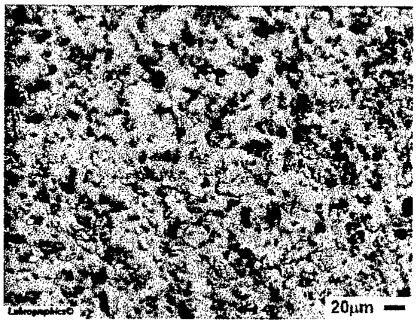

Fig 5 (a) Copper particles on a filtergram

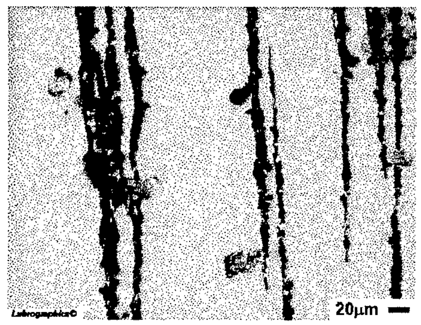

Fig 5 (b) Copper particles on a ferrogram

3.2 Atlas for Wear Severity Differentiation: Wear Particle Atlas 97 provides an exclusive filtergram-based wear severity differentiation component to assist judgement of machine wear severity levels with improved consistency. This component consists of a total 456 images and 121 application cases (i.e., examples). The wear severity levels are divided into either 10 levels for nonferrous component wear and ferrous rubbing wear mode (from Level 1 to Level 10) or 8 levels for those 'abnormal' ferrous wear modes (from Level 3 to Level 10), indicating wear deterioration processes from an initial wear up to a severe wear condition.

To improve the consistency of wear severity differentiation, the atlas firstly defines the "key features" for each severity level, which are the quantitative, measurable criteria based on size distributions and wear-mode-related type distributions of wear particles. Secondly, the atlas provides 1-5 wear particle examples at each severity level which approximately meet the criteria of the designated severity level. Each example consists of 4 representative wear particle images. By matching both measurable criteria and visible images, a random wear particle sample can be coded with a certain severity level.

For example, by means of the atlas, the metal particles of an oil sample are identified as:

- ferrous fatigue wear particles;
- the size of the fatigue wear particles is up to 100μm, and
- the concentration of the fatigue wear particles ranging between 50-100μm in size is about 60-80/ml.

These identified features match the designated criteria of Level 6 of ferrous fatigue wear severity as shown as follows:

- Up to **<u>100μm</u>** in size;

- Predominant laminar particles; and
- Concentration of laminar particles ranging between **50-100μm**: **>100/ml**

Further, the features of the wear particles of this sample are similar to those of the application cases (i.e., examples) of Level 6 in the atlas, see Fig 6. Therefore, the wear severity level of this oil sample can be differentiated as Level 6.

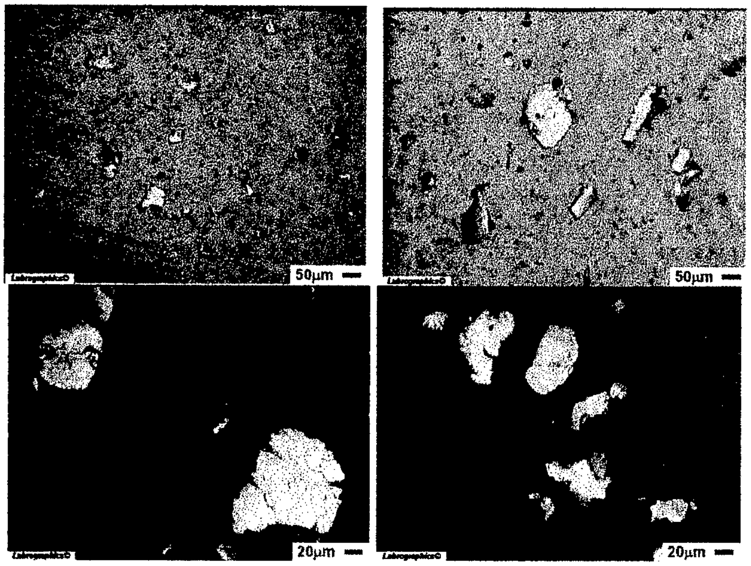

Fig 6 (a) Example 1 of fatigue severity level 6

This differentiated level, however, is a universal wear severity level. Depending on the criticality, operation environment and expected life of this machine, etc, this universal severity level may be defined as a "normal" or an "abnormal" or even a catastrophic condition. For example, if this sample is taken from an uncritical gearbox operated under a highly contaminated environment with a low design life, this severity level (Level 6) may be defined as a "mildly abnormal" wear condition. However, if this sample is taken from a critical hydraulic system, this level 6 may be specified as an "unacceptable" or even a "severe" condition. It is from this sense that the wear severity differentiation atlas provides an approximate yardstick of measuring wear severity levels of lubricated equipment, significantly contributing to consistent and standardised wear particle analysis.

3.3 Cleanliness Identification Of Lubricant: Wear Particle Atlas 97 also provides an ISO Cleanliness - Contaminant concentration reference for lubricant contamination monitoring. This reference consists of 10 sequential ISO Cleanliness levels from ISO 13/10 up to ISO 24/21, see Table 4. Each level contains 4 representative solid particle images grabbed from different areas of the filtergram with varied magnifications. This component can be used to correlate machine wear with lubricant contamination, and to estimate the cleanliness code numbers of some very dirty and/or water contaminated oil samples, which are usually unavailable or inconvenient for automatic particle counting. Fig 7 shows the solid particles corresponding to ISO cleanliness 19/16.

Table 4 Contamination levels and correspondent ISO Cleanliness

Contamination Level	ISO Cleanliness
Level 1	ISO13/10
Level 2	ISO15/12
Level 3	ISO16/13
Level 4	ISO17/14
Level 5	ISO18/15
Level 6	ISO19/16
Level 7	ISO20/17
Level 8	ISO21/18
Level 9	ISO22/19
Level 10	ISO24/21

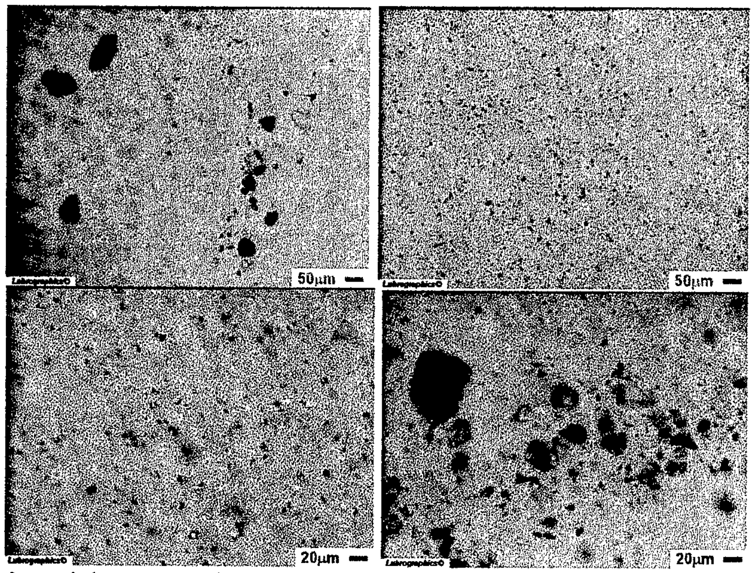

Fig 7 Solid particles on the filtergram slide corresponding to ISO Cleanliness 19/16

4 References

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