Measurement of Al–Si Cylinder Liners Using White-Light Interferometry and Image Processing on a Coordinate Measuring Machine

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Abstract
Al-Si alloys are widely used in internal combustion engines. Wear behaviour of Si-particles, which play an important role in oil consumption, mechanical power loss, friction, etc., is being investigated. Using a structure-oriented surface characterization approach, geometrical features of the Si–particles, e.g. size, height, become essential information. This paper presents a measuring procedure in order to carry out a wide study of these features at different positions in the cylinder liner. One of the challenging problems in the above approach is to detect the Si–particles using automated image processing. Because there are no significant differences between the height of the particles and the aluminium matrix on worn surface, the topographical data cannot provide enough information for detecting the Si–particles. For this reason, image processing is used to solve this issue.

Keywords:
Al-Si cylinder liners, structure-oriented characterization, wear analyse, image processing, Coordinate Measuring Machine (CMM)

1 INTRODUCTION

Al-Si alloys are being used in the manufacturing of internal combustion engines. Their main advantage is their lightweight in such a way that the power/weight ratio is above 1 kW/kg. Since aluminium does not have an adequate behaviour for this purpose, e.g. lack of wear resistance, several types of alloys with different metals have been investigated. Undoubtedly, Al-Si alloys with hypereutectic composition (containing 17-25wt.% Si) has been successfully used in cylinder crankcases for sport car competitions or high standard road car. The manufacturing of cylinder crankcases using Al-Si is based on three relevant techniques: Lokasil®, Alusil®, and Silitec®. For instance, 400.000 Lokasil® cylinder crankcases for Porche Boxster and 911 Carrera have been manufactured [1]. In addition, Al-Si has shown other advantage compared to cast iron engines [2], e.g. cooling, oil consumption, CO_2 emission. Environmental laws are limiting some of these parameters, therefore the application of Al-Si technologies to road car is continually increasing and new developments are proposing cheaper casting and surface preparation techniques.

These alloys are affiliated with metal-matrix-composites (MMC) and they own at least two phases, an aluminium matrix and crystal Si particles. Also other metals, for instance copper, are in the composition of the alloy. Other particles can be enclosed, but Si particles are the most important functional elements on the Al-Si-surfaces. Unlike other microstructured surfaces, such as laser-honing, the microstructures are irregularly distributed on the surface, because they appear by precipitation during the cooling process, and different microstructure properties can be obtained using different average cooling rates.

It is widely known that the particle height is a fundamental property for the tribological behaviour of the cylinder liner. The last stage in the honing of the Al-Si surface is carried out with the aim of uncovering the hard phase in the alloy, mainly Si–particles. This feature allows the identification of the particle height with the topographical data on a height histogram, which has different peaks for every phase. Therefore, a simple threshold between both peaks in the topography data is enough in order to do the identification for unworn cylinder liner surfaces. Frequently, Si–particles are exposed more than 1 µm from the aluminium matrix. Tribological studies of cylinder liner are already using size, aspect ratio, and height of the particles, which is frequently computed using histograms [3].

In the last years, a novel approach has been focused on characterization the surface wear using parameters with regard to the microstructures on functional surfaces. Whereas in the classical characterization, parameters are computed from the surface profile, e.g. Ra, Rq, Rz,..., in the structure-oriented parameter characterization approach [4], the geometrical features of the different structures presented in the surface are evaluated. Since wear mechanisms are either changing the height of particles or producing pits and scratches, the above approach is very appropriate to characterize Al-Si worn surfaces, because the particles, pits and scratches appearing on worn surfaces can be basically considered as stochastic structures. In order to use this approach, the detection of the particles has to be carried out. This process is a challenging task because of low particle exposure and intermetallic phases, which make Si-Particles detection difficult. The present work attempts to solve this problem using different sensors together with a Coordinate Measuring Machine (CMM), which is used to merge the information from both sensors.

2 MATERIAL

The CMM (OMS 553 HA) used in the present work is from Mahr Multisensor GmbH. The main feature of this machine is its micron accuracy, which enables to reach approximately the same spot using both sensors with an error in the same order like the lateral resolution of cameras. In this section, the descriptions of this device as well as its calibration are given.

2.1 Description

Two sensors are used with this CMM and they are described in the following:

- The reflection image of the surface is recorded using a camera with 30x magnification, a measuring field of 352x473 µm and an illumination ring with four independent sectors (figure 1).
- The topography is measured using a white-light interferometer with 20x magnification and a measuring field of 492x661 µm.

It should be mentioned, that this CMM is a prototype, the commercial version does not include the white-light interferometer. As a drawback, the camera and the white light interferometer are using the same measuring head, therefore they must be swapped.

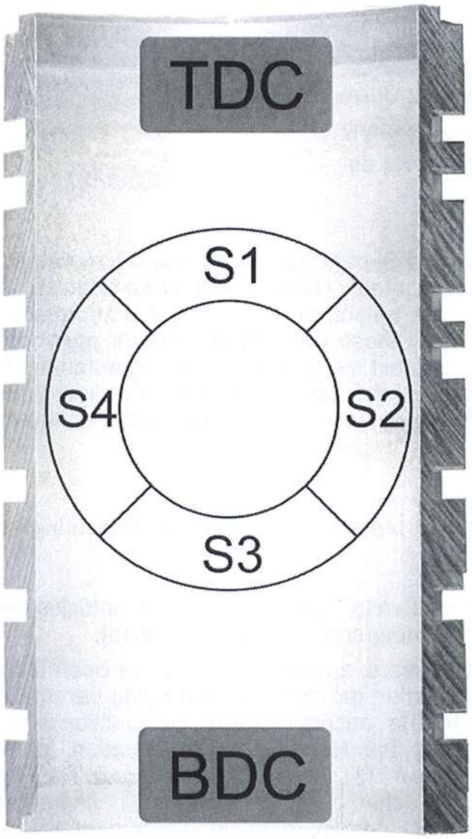

Figure 1: The cylinder liner was oriented respect to the sectors of the camera (S1, S2, S3, and S4). The top dead centre (TDC) is placed in the direction of S1 and the bottom dead centre (BDC) in the direction of S3, © IMR

2.2 Calibration

The calibration for the lateral resolutions of both sensors was carried out using a standard with several regions with periodic rectangular grooves. As a result, the lateral resolution of the camera is 0.616 µm and the lateral resolution of the white-light interferometer is 0.8615 µm.

Since data are recorded with two different CCD chips, the first step in the coordination of both images was to check whether a rotation error between both chips was present in the system. This calibration was carried out using the same standard as in above calibration. The images from both sensors were recorded in a spot where the grooves change their periodicity in order to match them line by line. These lines are fitted and their slopes are compared. During the data acquisition, sensors have to be swapped, therefore the previous calibration was carried out several times, checking these replacements are not introducing a rotation error in the measurements. As a result, no significance rotation error was found between both images (the errors were always less than 0.1 degrees).

Finally, relative coordinates for both sensors must be found. Besides rotation errors, the replacement changes also the relative position between camera and white-light interferometer. The proposed solution was to place a standard on the CMM table, which has circular grooves, and this standard is used to define an origin of the CMM coordinates after every replacement.

3 MEASUREMENT PROCEDURE

The measurement procedure can be split up into two stages: 2D and 3D. In the 2D stage, the camera is used to detect the particles and generate a mask; in the 3D stage, this mask is merged with the topography image recorded using the white-light interferometer. As a result, the mean height of every single particle from the aluminium matrix is computed.

3.1 2D Stage

In order to develop an automatic process for identifying Si-particles without any supervision, two kinds of illumination are used to increase the reliability and robustness in the identification. In spite of the use of a camera with different illuminations has already been proposed for inspection of cylinder liners, this problem was not properly addressed in literature. Evidently, other identification methods, e.g. EDS, etching, are more reliable, but they show several drawbacks, e.g. time consumption, high cost, damage of the topography, etc.

The image processing is carried out to detect the particle position using these two images:

- Bright Image (figure 2): This image is the classical reflection image, where the light beam is perpendicular to the surface, i.e. angle of incidence equal to zero.
- Dark Image (figure 3): This image is recorded using the ring illumination in the camera; the angle of incidence is not zero.

Using these two images, a simple image processing, based on the subtraction of both images, the candidate regions for Si-particles are detected. Roughly speaking, the dark image is used as a selective and adapted threshold, increasing the robustness of the detection at different positions. For very low wear rates, the intermetallic phases are able to keep a considered flatness. In these cases, it is also possible to avoid the identification as a particle, since their intensity in the bright image is clearly greater than for the Si-particles.

The main advantages using this method is the low time consuming and the relative high reliability of the automatic process in order to analyse a high number of measurements in a few minutes. Furthermore, it simplifies the statistical treatment in order to minimize any mistake in the identification and allows the coordination of the other sensors in the measurement.

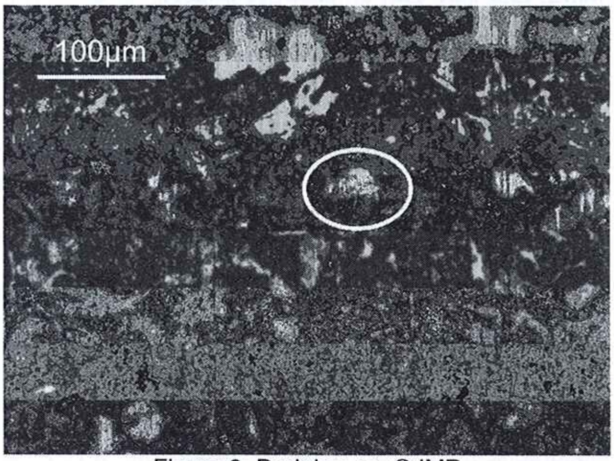

Figure 2: Dark image, © IMR

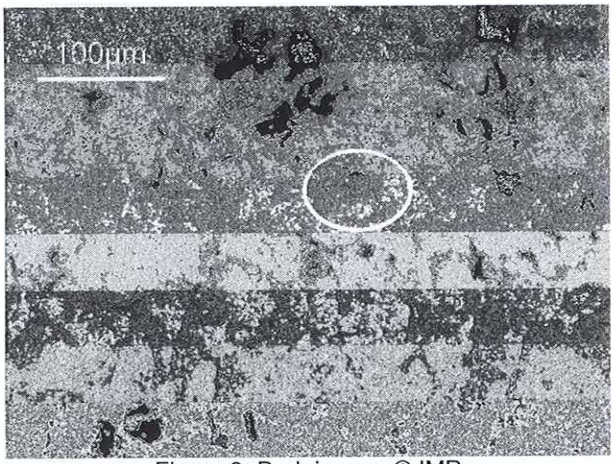

Figure 3: Dark image, © IMR

3.2 2D Stage

This stage consists in merging the particle mask with the topography. In order to avoid small error in the positioning system, an out-of-focus image, i.e. with no interference fringes, is recorded with the white-light interferometer and the bright image is resized in order to reach the same resolution as the white-light interferometer. With these two images, a cross correlation process is carried out in order to reach the same spot exactly.

Once the camera image has been placed within the white-light interferometer image, the topography is cut to the same size like the camera image, and the topographical information is reduced to the spot where the particles have been detected during the previous stage. The Si-particle mask image is resampled in order that it has the same resolution like the topographical image (figure 4).

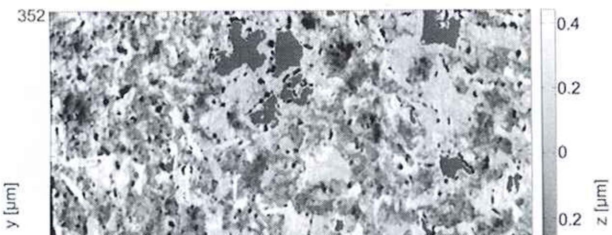

Figure 4: Topography of the above identified spot. In the right, the mask has been added, © IMR

4 MEASUREMENTS

The measuring procedure is tested in three places on the cylinder liner. This cylinder liner was used in a gasoline motor of a road car for 15000 h.

A software tool in MATLAB code was developed which's inputs are the two images recorded with the camera and the two images recorded with the white-light interferometer, i.e. the out-of-focus image and the topography.

The outputs of the program are the structure oriented parameters of Si-particles. In this work, we have computed a 2D parameter, the area ratio, and a 3D parameter, the mean structure height, but other parameters, e.g. aspect ratio, can be computed. Both parameters are defined as follow:

- Area ratio (AR):

$$AR = 100\frac{\sum_{i=1}^{n} A_{p,i}}{A},$$

where $A_{p,i}$ is the area of particle *i*, n is the number of particles, and A is the total measurement area

- Mean structure height(MSH):

$$MSH = \frac{\sum_{i=1}^{n} A_{p,i} H_{p,i}}{A},$$

where $H_{p,i}$ is the mean height of particle *i*.

The table 1 shows the result of five measurements.

Measurement	AR (%)	MHS (nm)
1	3	85
2	3.28	114
3	1.65	221
4	2.15	152
5	4.01	120

Table 1: Measurement results, © IMR

5 SUMMARY

A measuring procedure has been developed in order to identify the silicon particles and compute their properties, e.g. area ratio, mean height. For this aim, two sensors have been used: a camera and a white-light interferometer. The identification has been carried out using two different reflection images, and this technique has been adequately addressed. With a CMM, both sensors can be placed at the same spot, and an image processing allows the merging of the data from them. The full process, the data acquisition and the image processing, can be automated.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] E. Köhler, J. Niehues, Aluminium-matrix composites materials in combustion engines, in: K. U. Kainer (Ed.), Metal Matrix Composites, Wiley-VCH, 2006, pp. 95–109.

[2] M. Dienwiebel, K. Pöhlmann, M. Scherge, Origins of the wear resistance of Al-Si cylinder bore surfaces studies by surface analytical tools, Tribology International 40 (10-12) (2007) 1597 – 1602.

[3] M. Elmadagli, A. Alpas, Progression of wear in the mild wear regime of an Al-18.5% Si (A390) alloy, Wear, 261, (2006) 367 – 381.

[4] A. Weidner, J. Seewig, E. Reithmeier, 3D roughness evaluation of cylinder liner surfaces based on structure-oriented parameters, Measurement Science and Technology 17 (3) (2006) 477.