IMAGE ANALYSIS OF INCLUSIONS IN CAST CARBON STEEL

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ABSTRACT

Quantitative image analysis of inclusions in two aluminium-deoxidised and calcium-treated carbon steel castings was carried out. The suitability and limits of the method in a material with relatively small amount of small size inclusions were studied. To study the reproducibility of the analysis, the analysis was carried out in two laboratories. Common pixel size, total analysis area and number of images were used, but the image sites were chosen independently at the laboratories.

The inclusion analysis results of both laboratories show a higher inclusion content for steel B that had higher alloy and impurity element levels. The area fractions of inclusions measured using image analysis were 1.3 - 2.2 times higher than the oxide and sulphide amounts calculated based on the steel compositions. Micro-porosity in the steels was treated as inclusions and thus it raised the inclusion fraction obtained in the image analysis. A major difference exists between the results of the laboratories in the amount of large inclusions. The 1-mm^2 analysis area was found to be too small for reproducible analysis, although only a local inclusion distribution in the material was analysed. Good quality of specimen preparation was found necessary, because discrimination between inclusions and artefacts in image analysis is difficult.

KEYWORDS

Cast carbon steel, Inclusions, Quantitative metallography, Image analysis.

INTRODUCTION

In the research project 'The Effect of Inclusions on Surface Quality and Mechanical Properties of Steel Castings', the effect of ladle treatments of steel melt on non-metallic impurities and hence mechanical properties of steel castings was studied. To quantitatively determine the amount and distribution of inclusions in the castings, image analysis was found necessary. The suitability and limits of the method in a material with relatively lean content of small size inclusions were researched. To study the reproducibility of the analysis, the analysis was carried out in two laboratories: VTT Manufacturing Technology and Mica laboratory at the University of Liege. The work was done as collaboration in COST 517 Action.

MATERIALS AND METHODS

Materials and specimen preparation

The materials examined in this study are two carbon steels of WCC/LCC cast steel grade as specified in ASTM A 352/A 352M standard. The steel melt was aluminium-deoxidized and calcium-treated Deoxidising the steel melt with aluminium. Deoxidation with aluminium, which is a normal practice in steel foundries, can, however, cause harmful types of non-metallic impurities like grain boundary rows or macroscopic clusters of alumina inclusions in the casting. By calcium-treating of aluminium-deoxidised steel melt, alumina and sulphide inclusions can be modified into calcium aluminates that have a more advantageous shape and distribution in the steel. Calcium aluminate is a compound structure inclusion that has an (Al,Ca)O core and a (Ca,Mn)S shell. Compared to alumina inclusions, calcium aluminates have a lower tendency to form large inclusion clusters and are more uniformly distributed in the steel.

The compositions of the steels used are shown in Table 1. Steel A has a higher carbon content and lower manganese content than steel B. A higher content of aluminium was used for deoxidation in steel A. Higher oxygen and sulphur levels were measured in steel B, referring to higher inclusion content. A calculation based on the steel compositions was made to estimate the inclusion amounts that were 0.09 volume-% in steel A and 0.13 volume-% in steel B. It was not possible to take into account the calcium aluminate formation in the calculation, so the inclusions were treated as oxides and sulphides.

Table 1. Compositions of castings A and B. Oxygen content is the average value of the total oxygen content in three 1-g samples analysed with Leco gas analyser. Other elements were analysed using an optical emission spectrometer.

	C	Si	Mn	Al	Ca	S	O	Fe
A	0.22	0.34	0.77	0.080	0.0031	0.009	0.009	balance
B	0.15	0.36	1.17	0.026	0.0036	0.011	0.016	balance

Samples for image analysis were taken of identical 60 kg flat bar castings of steels A and B. The samples were taken from identical sites at a depth of 25 - 35 mm below the surface of the castings. The inclusion distribution through the whole casting is not uniform and the sample does not represent inclusion distribution in the whole casting. The specimens were quenched and tempered. For the image analysis, a surface area of roughly 200-mm^2 for each specimen was polished. For final polishing, 1-μm diamond was used.

Acquisition of the images

To acquire as good a reproducibility of the analysis as possible, the basic parameters of image acquisition have to be common in the two laboratories. After preliminary examination of the samples, the following parameters were chosen for use in both laboratories:

- Pixel size of the images was 0.17 μm.
- Total analysis area of each sample was 1 mm^2, consisting of 27 - 28 images. The image sites were chosen randomly and independently at the laboratories. However, the sites were chosen to uniformly cover the 200-mm^2 polished surface of each sample.

At the ULg, the images were acquired with a black and white cooled CCD camera, with a high resolution (1280 by 1024 squared-pixels) and a high sensibility (at 500 nm: 40 % quantum efficiency), used with an optical microscope.

The magnification retained for the inclusion analysis was 110 times. (50 times objective and 2.5 times photo eyepiece). Therefore, one pixel side was equal to 0.17 micrometer. One image (1280 by 1024 squared-pixels) covers a field of 217.6 micrometers in length by 174.08 micrometers in height. A series of 28 images was acquired, thus giving a total analysed area of about one square millimetre.

At VTT, the images were taken with an optical microscope (Leitz) using 80 times objective and negative 35-mm film camera. The negatives were scanned with Polaroid 35 film scanner to form 1172 x 1080 pixel images (resolution 1300 dbi). Thus the pixel size 0.17 μm was reached.

At Mica, two series of images were acquired for each sample. The images of the first series contained many artefacts due to inadequate surface cleaning and polishing quality. For the second series, samples were very carefully polished and cleaned before the acquisition. At VTT, one series of images was acquired.

Treatment of the images

Under the microscope, some lighting defects were observed and needed to be corrected before the image treatment, since they affect particle extraction [1]. Figure 1 shows an example of the lighting correction. The treatment of this kind of images is relatively simple because the inclusions are black particles in a bright matrix. Segmentation is followed by erosion and reconstruction [2] to delete noise and small defects. This kind of lighting correction was made at Mica laboratory.

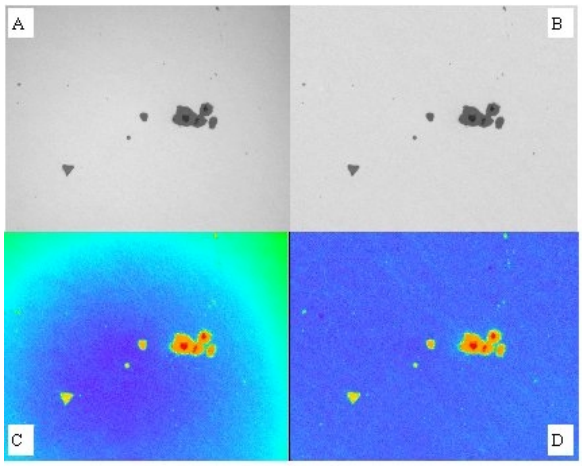


Figure 1. Images before and after correction of lighting defects (Mica laboratory). (A) Grey scale image before correction, (B) Grey scale image after correction, (C) Rainbow look up table image before correction, (D) Rainbow look up table image after correction.

At VTT, the colour adjustment of images was made using Paint Shop Pro software.

Image analysis and measurements of the inclusions
The image analysis was done at Mica using Aphelion software and at VTT using Optilab Pro software.

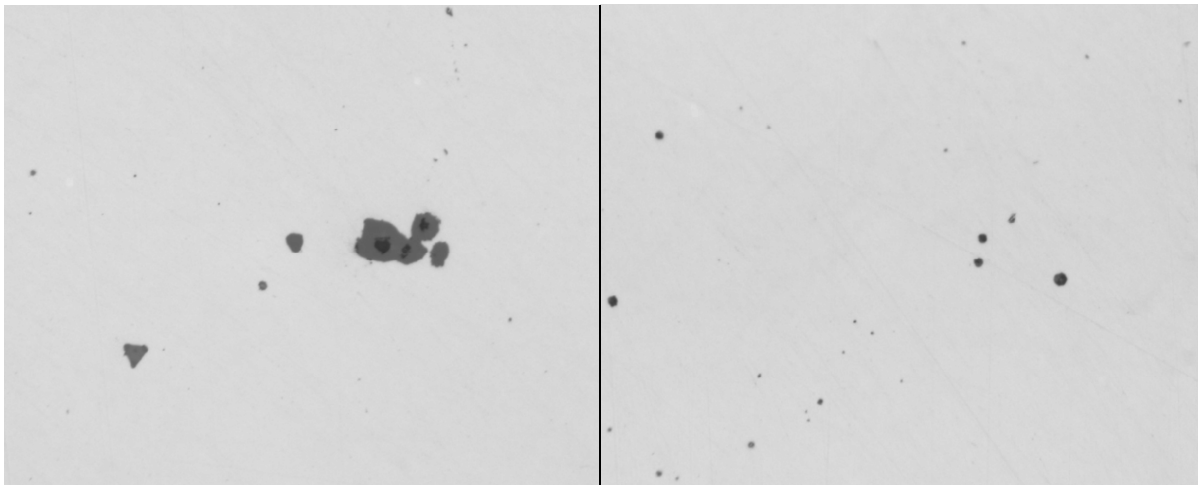
The following parameters measured in the image analysis are described in the results:

- The number of inclusions per square millimetre.
- The inclusion size described by the equivalent disc diameter. $diam = 2 * \sqrt{\frac{Inclusion\_Area}{\Pi}}$
- The area fraction of inclusions.

If their area is smaller than 25 squared-pixels, the inclusions cannot be measured with sufficient precision. Thus, only particles with an equivalent diameter larger than 1 μm can be reliably characterised using the chosen magnification. The results, however, include the category of smaller than 1 μm equivalent-diameter inclusions, in order to roughly illustrate the amount of the smallest inclusions.

RESULTS

Figure 2 shows two of the 28 images that form the ULg series 2 of steel A. Image (a) contains a small inclusion cluster rated as one inclusion. The compound structure of the large inclusions can be clearly observed. The area fraction of inclusions in image (a) is exceptionally high. The number of inclusions in different size categories is illustrated in Figure 3 and the total number of inclusions in Table 2. The cumulative area percentage of inclusions in different size categories is shown in Figure 4 and the total area percentage in Table 2.



a b

Figure 2. Two images used in the inclusion distribution measurement of steel A. The area percent of inclusions is 1.4 % in Image (a) and 0.29 % in Image (b). Magnification - 368 times.

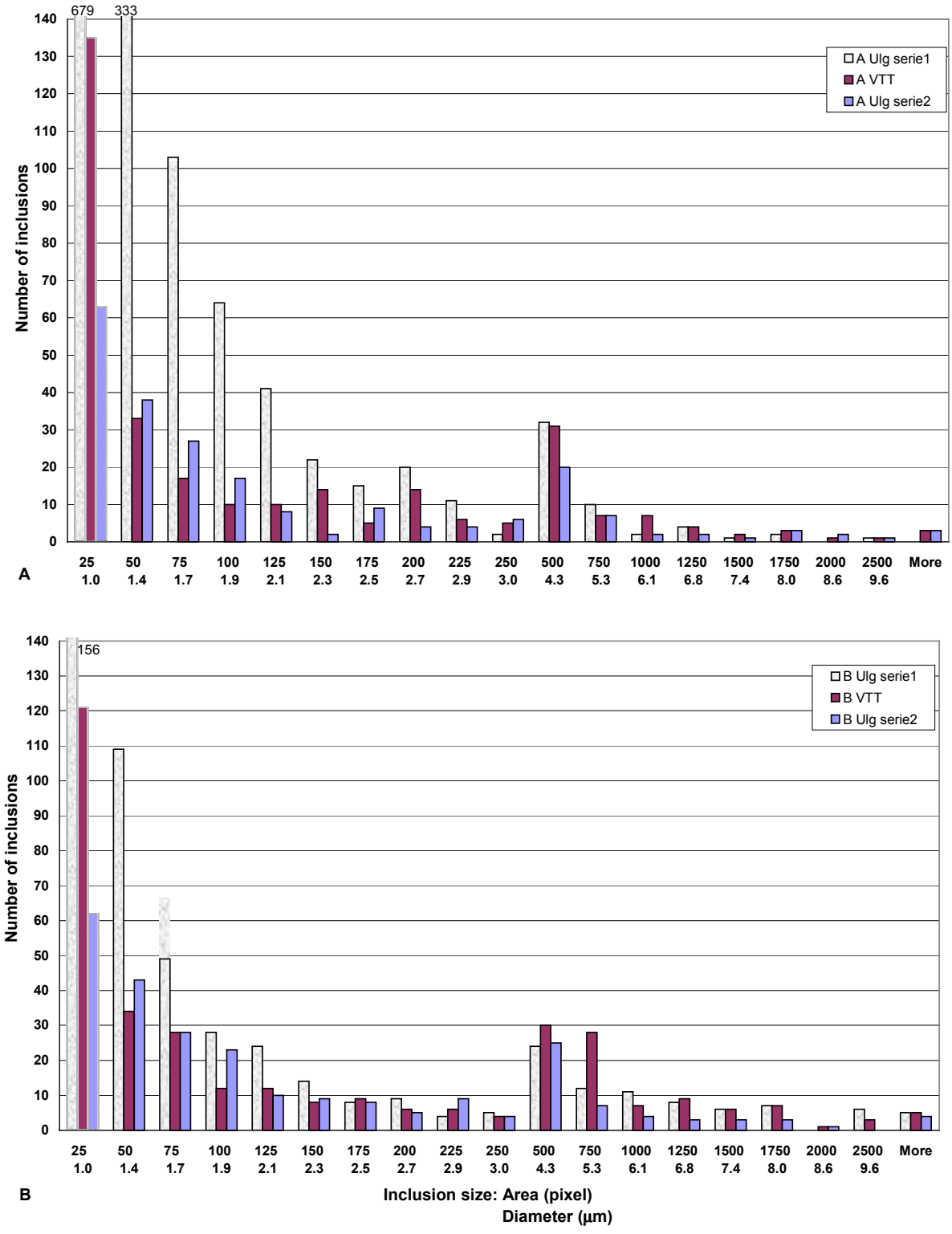


Figure 3. Number of inclusions in an area of 1 mm^2 in steels A and B. Size categories: 1-25 pixels, 26-50 pixels, etc. The category of less than 25 pixels is not considered a reliable result.

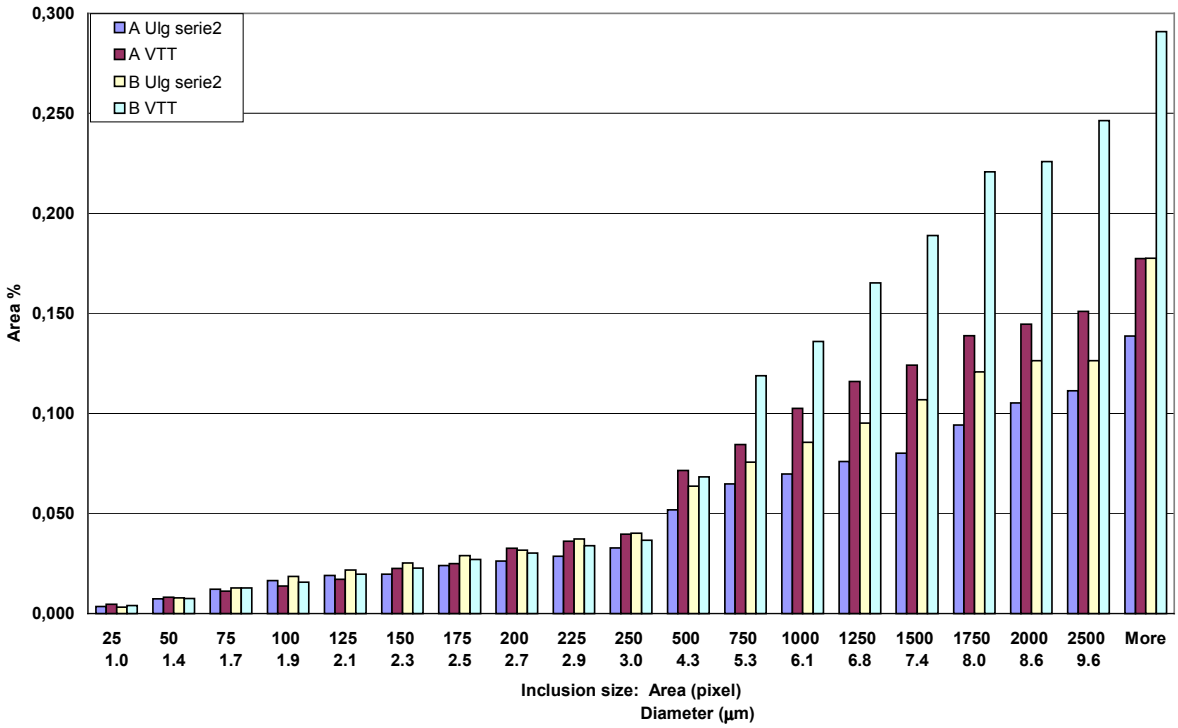


Figure 4. The area percentage of inclusions in an area of 1 mm^2 in steels A and B. Size categories: 1-25 pixels, 26-50 pixels, etc. Cumulative values.

Table 2. Total number of inclusions, mean equivalent diameter of inclusions and total area percent of inclusions in steel A and B. Plain values include inclusions more than 25 squared-pixels in size whereas values in brackets also include measurements of inclusions less than 25 squared-pixels in size.

	A, ULg 2	A, VTT	B, ULg 2	B, VTT
Total number of inclusions	156 (219)	173 (308)	189 (251)	215 (336)
Mean diameter of inclusions, µm	3.32 (2.84)	3.58 (2.71)	3.43 (3.00)	4.16 (3.35)
Total area percent of inclusions	0.14	0.17	0.17	0.29

DISCUSSION

Good quality of specimen preparation was found to be necessary, since discrimination between inclusions and artefacts in image analysis is difficult. Good preparation includes high quality polishing as well as careful cleaning of the samples between polishing stages and after final polishing. In ULg series 1 inadequate surface quality of the specimens was found to cause overestimation in the number of the smallest particles.

The analysed materials contained a high proportion of small inclusions that could not be measured precisely enough using the pixel size 0.17-µm. In ULg series 2 and in VTT series, 24 - 44 % of the measured inclusions are below the lower limit of reliably measured inclusions, 1-µm (25 squared-pixels). This can cause a remarkable error in the number of inclusions but not in the area fraction of inclusions, since the smaller than 1-µm inclusions have a minor weight in the area fraction.

A major difference exists between the results of VTT and ULg series 2 in the amount of inclusions larger than 4.3 μm of equivalent diameter (500 squared-pixels). The effect of too small an analysis area causes scattering, especially in the results of large inclusions. The number of large inclusions is too small for reproducible analysis.

The area fractions of inclusions measured using image analysis were generally higher than the oxide and sulphide amounts calculated based on the steel compositions. In ULg series 2, the values measured with image analysis were 1.3 -1.5 times higher and in VTT series 1.8 - 2.2 times higher than the values of the oxide and sulphide calculation. The steels contained some microscopic porosity, which was not possible to separate from the inclusions in the image analysis. The porosity thus raised the inclusion fraction values in both laboratories. It must also be noted that the calculation based on composition could not be done in an exact way.

The inclusion analysis results of both ULg and VTT show a higher inclusion content for steel B than for steel A. This was also expected, as the oxygen and sulphur levels analysed in steel B were higher than those of steel A and also the calculation based on composition showed a higher inclusion level in steel B.

An analysis area of larger than 1 mm^2 was found to be necessary for reproducible analysis, although only a local inclusion distribution in the material was analysed. A more general determination of inclusion content in a large amount of steel is usually done according to standard like ASTM E 45 [3]. In the ASTM E 45 standard, the total inspection area is 160 mm^2. In a traditional inclusion rating as described in the standard, relatively low magnification and resolution are allowed and 160 mm^2 area is covered by 320 images, whereas in the case described in this paper more than 4000 images had been needed for a 160 mm^2 total image area. Using a modern image analysis system based on CCD camera acquisition and powerful image processing, it is possible to rapidly analyse large numbers of images.

REFERENCES

[1] Pirard E., Lebrun V., Nivart J.-F. : Optimal acquisition of video images in reflected light microscopy; Microscopy and Analysis, July 1999.
[2] Russ J.C.: The Image Processing. CRC Press, 1999.
[3] Standard Practice for Determining the Inclusion Content of Steel. ASTM E 45.