Minerals Engineering 55 (2014) 111–124

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Automated relief-based discrimination of non-opaque minerals in optical image analysis

A. Poliakov *, E. Donskoi [1]

Processing and Agglomeration, CSIRO CPSE, PO Box 883, Kenmore, QLD 4069, Australia

ARTICLE INFO

Article history:
Received 27 May 2013
Accepted 17 September 2013
Available online 26 October 2013

Keywords:
Optical image analysis
OIA
Non-opaque
Relief
Characterisation
Automated mineralogy

ABSTRACT

Ore characterisation is important in order to understand the quality of ores and their behaviour during downstream processing. Many significant ore characteristics can only be determined through the use of various imaging techniques. Optical Image Analysis (OIA) is one such technique and is particularly attractive for many applications due to its low cost and high resolution. However OIA also has some limitations, one of which is the difficulty with discriminating non-opaque minerals. Some non-opaque minerals, such as quartz, are typical gangue minerals in certain types of iron ores. Even though in many cases quartz particles can be easily seen and attributed by mineralogists in polished sections, their automated discrimination has always been an issue, the reasons for which are discussed in this article. The ability to automatically discriminate quartz and other non-opaque minerals would significantly increase the value of OIA for the mineral industry.

This paper describes a novel method of discriminating non-opaque minerals in the sample by their optical relief, which results in visible borders between the mineral and the epoxy resin mounting medium. An algorithm for such discrimination that has been developed for the CSIRO Mineral4/Recognition4 OIA software package is described. The algorithm is based on dynamic thresholding of the image with subsequent cleanup and enhancement to reliably determine borders between non-opaque particles and epoxy and on subsequent attribution of image areas created by these borders to either the non-opaque mineral or the epoxy resin. Further, this article discusses difficulties that may arise when applying this algorithm due to sample peculiarities and describes algorithm enhancements incorporated in Mineral4 in order to overcome these issues. The resulting software is capable of reliably discriminating non-opaque minerals in a variety of samples, including iron and manganese ores.

1. Introduction

Extensive mineralogical and textural characterisation of different ores is a key element in the development of downstream mineral processing routines in order to understand and attempt to predict an ore's behaviour during mineral processing (Donskoi et al., 2007a,b, 2008a,b, 2012). A number of significant ore characteristics, including mineral associations, mineral liberation and grain size distribution, can only be obtained by using imaging techniques (Donskoi et al., 2007a). The two main techniques currently used in mineralogical applications are Scanning Electron Microscopy (SEM) (Gottlieb et al., 2000; Maddren et al., 2007) and Optical Image Analysis (OIA) (Donskoi et al., 2011; Gomes and Paciornik, 2008). Both methods have their benefits and limitations. In particular, OIA systems have significantly lower capital and maintenance costs and are capable of providing much better resolution at comparable analysis times (Donskoi et al., 2011). They are also specifically attractive for studies of ores consisting of minerals with similar chemical composition, such as iron oxides and oxyhydroxides, which have different optical properties (Pirard and Lebichot, 2004; Pirard et al., 2007). In addition, OIA systems allow characterisation of grain structure of the same mineral (Gomes et al., 2010; Iglesias et al., 2011). This makes OIA a valuable tool in iron ore characterisation where different mineral polymorphs have different processing outcomes (Pirard, 2004; Donskoi et al., 2008a,b). On the other hand, identification of different minerals with reflectivities close to each other or to epoxy is an obvious problem that restricts the possible use of OIA in certain areas (Launeau et al., 1994; Neumann and Stanley, 2008). In recent years, with the rapid progress of computing and digital imaging technologies, there has been a dramatic improvement in the ability of OIA to discriminate minerals with very similar reflectivities when viewed with standard reflected light optical microscopic techniques (Donskoi et al., 2010). This improvement resulted from the increased sensitivity of digital cameras, the switch to colour rather than greyscale

* Corresponding author. Tel.: +61 7 3327 4143; fax: +61 7 3327 4682.
E-mail addresses: andrei.poliakov@csiro.au (A. Poliakov), eugene.donskoi@csiro.au (E. Donskoi).
[1] Tel.: +61 7 3327 4158; fax: +61 7 3327 4682.

0892-6875/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mineng.2013.09.014

images, and increased computing power making it possible to utilise complex image analysis routines, thus providing much better discrimination of minerals based on their reflectivity and texture.

One particular example of problematic mineral identification when using OIA is the discrimination of non-opaque minerals (Donskoi et al., 2011; Neumann and Stanley, 2008). When the thickness of such a mineral in a mounted sample is small or the opacity is near zero it is the underlying material (mounting epoxy resin in most cases) that is being imaged. Significant improvements in camera sensitivities allowed for some non-opaque minerals like apatite, amphibole, calcite and garnet to be recognisable using OIA (Lane et al., 2008). However some non-opaque minerals which, when imaged, show reflectivities very similar to that of the epoxy resin mounting medium, are still quite problematic for automatic discrimination by OIA.

A typical example of such a non-opaque mineral, a gangue mineral particularly abundant in iron ores of certain types, is quartz. The very limited ability of traditional threshold-based OIA to automatically identify quartz has been one of the biggest problems in the application of OIA to iron ore characterisation for a long period of time. Several approaches, as described further, have been suggested to overcome this restriction. Some of those approaches can provide good results in certain cases, however they often require complex sample preparation and image acquisition techniques and are not applicable to the whole range of possible tasks. For example, thin section imaging (Hunt et al., 2010) cannot be used for the characterisation of iron ore fines because the section thickness is the order of the size of fines and is greater than the usual textural element dimensions for the majority of iron ores. This technique also requires multiple images being taken over the same sample area which assumes a high level of microscope automation and complex acquisition and image analysis routines.

There also have been attempts to improve quartz identification by making simple changes to polished block preparation, such as selecting the most suitable brand of epoxy resin and/or impregnating it with dyes, but they have not produced acceptable results to date (Neumann and Stanley, 2008). The authors of this paper are considering alternative sample preparation methods to further improve non-opaque mineral discrimination from epoxy resin by automated OIA. These include mixing ultrafine material with the epoxy resin to create a highly textured epoxy that can be automatically segregated from non-opaque mineral areas, which will not display this texture because the epoxy underneath will be distorted and/or out of focus. The textural identification module recently developed for the Mineral4 software package (Donskoi et al., 2013) could then be used to identify non-opaque mineral areas. This method is still under development and at present it is worth exploring other opportunities that do not negate one of the main advantages of traditional OIA, that is, its simple and easy sample preparation and imaging techniques.

It is particularly important to note that in many cases OIA-based mineral identification can be more accurate than that performed by a mineralogist because, although the human eye is very efficient at seeing relative differences between greyscale or colour reflectivities, it is not as adept as OIA in determining their absolute values. It leads to the well known optical phenomenon where an object viewed on a black background is perceived as being brighter than another object viewed on a white background, while in fact it is darker. During mineral identification by a mineralogist, this phenomenon can result in the different identification of the same grains of minerals, depending on whether they are embedded in lighter or darker matrices. Although experienced mineralogists can make adjustments during identification, based upon their knowledge of typical mineral textures and associations, it is not unusual to see them disagreeing about the particular features of a given sample. OIA methods that are based on the absolute reflectivities of minerals rather than human perception of reflectivities are free from such bias. However in the case of quartz, OIA often fails to recognise particle areas that mineralogists have no problem in identifying. This is due to the ability of the trained human eye and brain to recognise familiar patterns and come to conclusions on their broader meaning.

Fig. 1a shows an image of a cross-section of an epoxy resin mounting block with embedded iron ore fines containing quartz and two attempts to separate quartz grains from epoxy resin by colour thresholding, which is a combination of three thresholdings (Otsu, 1979) in RGB colour channels. The epoxy in this example has been impregnated with dye, which makes quartz, as well as non-uniformities in the epoxy, in most cases caused by particle areas underneath the surface, more visible to the human eye. It can be easily seen that, depending on the choice of thresholds, the result is either almost no epoxy resin identified as quartz, but significant areas of quartz not identified as well (Fig. 1b), or almost entire quartz particles identified but very significant portions of the epoxy resin also identified as quartz (Fig. 1c). In Fig. 1b the false readings of "quartz pixels" in epoxy can be mostly eliminated by applying cleanup procedures such as scrapping, however this operation will eliminate even more quartz areas. In Fig. 1c, most (but still not all!) of the quartz has been identified, however the incorrect identification of epoxy resin as quartz is so significant that it cannot be reliably scrapped or cleaned up in any other way, thus resulting in unsatisfactory levels of misidentification. If regular epoxy resin is used, the result of the thresholding procedure is very much the same, the only difference being that the thresholding is even harder to perform because quartz areas are less readily distinguishable from the epoxy resin by the operator.

2. Border-based discrimination overview

From the images in Fig. 1 it can be clearly seen that in many cases, such as the one presented in the image, even if there is a difference in the reflectivity between epoxy resin and quartz, or another non-opaque material, that difference is not enough for them to be reliably segregated by thresholding. It is, however, worth mentioning that for a human observer there is no difficulty in determining non-opaque particles in this and similar images. There are two main factors allowing the observer to perform identification of those particles. Firstly, the border separating non-opaque particles from epoxy is often reasonably well visible and, even if it is optically discontinuous, the human brain can easily reconstruct the entire border. Secondly, the border divides the "epoxy-like" area of the image into two areas, one of which is essentially contained within another. For the human brain the combination of these factors leads to an easy conclusion that the outer area is epoxy itself and the inner area is a non-opaque particle embedded in it. The presence of other particles, whether opaque or non-opaque, embedded in the epoxy, can make identification even easier. It is important to mention that in the absence of references provided by other particles and/or distinct shapes, distinguishing quartz from epoxy can be very hard or even impossible even for an experienced mineralogist. Fig. 2 provides a somewhat trivial example obtained by selecting a rectangular area from the original image with a clearly visible quartz grain, which roughly corresponds to imaging of the same sample at higher magnification with the same image size in pixels. Although the increase in magnification may be beneficial for providing a clearer understanding of the mineralogy or texture of other particles represented in the sample, it makes it harder to recognise non-opaque mineral areas on individual images because the point of reference can be lost. Even though it is nearly obvious that Fig. 2b shows the border between a non-opaque mineral and epoxy resin, the observer has less idea which area