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Porosity assessment of suspension and saturated composite castings with the use of microscopic examinations

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Abstract

Good quality in composite castings can be confirmed primarily by their user. The producer is obliged to create a good product that meets the user's needs that should undergo quality control. Omission of technological procedures and improper quality control may result in various defects like porosity. This paper presents the characteristics of the casting defect, namely porosity, with a particular focus on porosity in suspension and saturated metal composites. This defect is different, specific to composite castings, making its identification very difficult. The aim of the study is to detect and describe porosity in composites with the use of microscopic and submicroscopic examinations. The assessment of the porosity of the microstructure of composite castings allowed for the formulation of the following conclusions: in addition to the porosity that occurs in castings of classic materials (cast steel, cast iron, and non-ferrous metal alloys), metal composites also distinguish between primary and secondary agglomerates, leaving the reinforcement space not filled, occluded bubbles, and separated gas bubbles.

Introduction

The developing shipbuilding and automotive industry, and at the same time the impending fuel and ecological crisis, forces the search for new and better materials than those currently used and for new technologies for their production (Przestacki & Chwalczuk, 2017). This is related not only to the improvement of operating conditions, in extending the service life of machines and devices, but also to cheaper and less environmentally harmful methods of obtaining them (Orłowicz et al., 2015). At the same time, the phrase "new and better" refers primarily to the ongoing search for materials of better quality, with a limited number of defects and mechanical properties, while reducing their weight, which significantly affects the operating conditions such as combustion conditions, exhaust gas toxicity (Kazienko & Chybowski, 2020), efficiency, and service life.

These requirements are increasingly often met by composite materials (Kawalec et al., 2008), produced by casting methods, reinforced with ceramic fibers or particles in a random manner, and with a metal matrix. Light metal alloys (aluminum, titanium, magnesium) are most often used for the matrix due to their favorable properties (Przestacki & Chwalczuk, 2017). The reinforcement is mainly made of ceramics (aluminosilicates, SiC, B_4C, carbon, graphite, diamond). The unquestionable advantage of composite materials, which other materials lack, is the ability to control these properties. This can be achieved, for example, by the appropriate selection of the matrix and reinforcement. This feature of composite materials allows them to have a very wide range of applications. For example, they can be used in the automotive industry as a material for a vehicle body, civil engineering as a reinforcement material, shipbuilding as material for combustion engine pistons, and electrical engineering as a construction material for electrical cabinets and switchboards. Composite materials produced by casting methods (so-called "ex-situ" methods) can be divided into two groups in terms of technology:

- Suspension composites – where the liquid matrix is mixed, most often with reinforcement particles, mechanically in accordance with the diagram shown in Figure 1a.
- Infiltration composites – where the matrix is saturated with liquid metal (usually under pressure) of a properly prepared reinforcing profile made of short fibers or particles (Figure 1b).

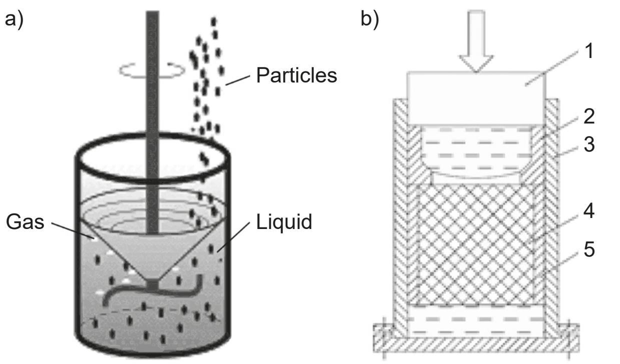

Figure 1. Production of cast metal composites: a) suspension, b) infiltration (1 – punch, 2 – piston, 3 – sleeve, 4 – ceramic shaped piece, 5 – reinforcement cavity, b) composite fracture with infiltrated reinforcement)

When considering composite materials produced by casting methods, porosity is often referred to. Porosity is always present in castings (Orłowicz, Trytek & Malik, 2013). It can be described as a broadly understood term for small gas bubbles, spongy-type shrinkage porosities, and sometimes non-metallic inclusions (PN-ISO 10049:2019). In the case of castings made of classic materials, such as cast steel, cast iron, and non-ferrous metal alloys, it is properly classified and subject to assessment (Jadhav and Jadhav, 2013). According to the standard (PN-85/H-83105) and Falęcki, porosity belongs to the group of internal defects where we distinguish as blisters, gas porosity, shrinkage cavity, and microshrinkages (Major-Gabryś, 2019). However, in the case of composites, we deal with its various forms resulting from the specificity of the system (the presence of components) and technology. Therefore, the methods of its detection and identification are very important from the point of view of the quality of the manufactured products (castings). Both types of composites (suspension and infiltration) are characterized by porosity understood, as already described, as a casting defect (Falęcki, 1997). However, the mechanism of its formation and its type depends on the technology.

In the case of a suspension composite, changing the curvature of the liquid matrix metal during mixing and giving the reinforcement particles a specific velocity vector (as shown in Figure 1a) enables their introduction and distribution in the matrix. Gas bubbles may be introduced into the suspension during the addition of the particles or mixing as a result of the surface disturbance of the composite bath (due to vigorous mixing). This causes the so-called primary and secondary particle agglomerates. These agglomerates form a network of interconnected pores and gases (Gawdzińska et al., 2017). In addition, the particles not wetted by the matrix create a gas gap between them or absorb gases from the baths on their surface and aggregate into clusters. During the production of these composites, during mixing, the reinforcing phase should be uniformly distributed in the entire volume of the liquid metal. It is also associated with the breakdown of agglomerates of the reinforcing phase (particles). Intensive and prolonged stirring, however, leads to a thickening of the composite suspension. This may result in an increase in the number of porosity defects of various types.

However, in the case of saturated composites, where we are dealing with so-called "rigid" reinforcement placed in the mold while filling the mold and saturating the reinforcement, the phenomenon of gas occlusion formation can be observed, a diagram of which is shown in Figure 2. During the impregnation process, in addition to overcoming the infiltration pressure and the flow of metal into the channels of the shaped piece with the most favorable flow conditions, these places are located in the areas with a locally reduced density of fiber "clumping" (Gawdzińska et al., 2017), and the filling of the reinforcement areas with increased hydraulic resistance (Grabian, 2001). In this crucial stage, filling capillary spaces formed by fibers in contact or close to each other takes place. Insufficient saturation between reinforcement elements should also be classified as porosity because these spaces are filled with gas.

In this study, microscopic and submicroscopic metallographic examinations were used to detect and identify porosity defects. This is to confirm the

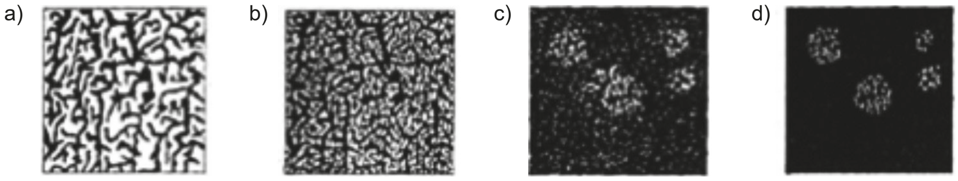

Figure 2. Diagram of the formation of gas occlusions when saturating composite reinforcement with liquid matrix metal (Jackowski, 2002)

good quality of the product, composite castings, and to answer the research question: will structure analysis using microscopic tests allow for a determination of specific types of porosity in composites?

Research material and methodology

The research material consisted of composite suspension and infiltration castings made in accordance with the principles presented in the works (Gawdzińska, Chybowski & Przetakiewicz, 2017; Sika et al., 2020) and Figure 1. Aluminum alloy is a composite matrix. The structural analysis was performed using microscopic and submicroscopic metallographic examinations.

Metallographic studies using a light microscope

These studies are carried out at various magnification, up to 4000 times, on properly prepared specimens (microsections). Preparing the samples is, in the case of composites, very difficult, due to the difference in the properties of the material components. Metallographic examinations with the use of a light microscope make it possible to distinguish structural components and determine their quantity, distribution, size, shape, and porosity.

The studies in this work were carried out using the Neophot 2 light microscope. Observations were made at magnifications from 100 to 1200 times. Samples for structural testing after electrical discharge cutting were mechanically ground on water-resistant abrasive papers and then polished with an aqueous suspension of Al_2O_3 polishing powder or a diamond suspension using a Struers grinder. The microsections were not digested. In some cases, when there were difficulties in the unambiguous identification of defects, the samples were sprayed with silver oxide.

Submicroscopic metallographic studies performed using an electron microscope

These studies can be carried out using a transmission electron microscope (rarely used and not very useful in examining the structural defects of metal composite castings currently, due to complicated preparation) and reflection electron microscope, in which some of the electrons of the incident beam are backscattered from the surface of the thick sample layer (surface topography), and the image is created in a scanning system. The magnification range used in these studies depends on the quality (resolution capabilities) of the microscope and can reach up to a million times.

The microsections for this study can be prepared in the form of debris or fractures. These studies allow for observing very small separations of various phases and structure defects, such as dislocations and improper combinations of composite components. They can also supplement and confirm studies carried out on the light microscope due to the wider possibilities related to magnification or constitute the basis for further research using X-ray microanalysis, for example.

In this work, metallographic studies were carried out on the JEOL JSM 6100 and Philips XL30 (LaB6) scanning electron microscopes. Magnification was selected individually. The samples were in the form of undigested microsections. The slides were mostly sprayed with silver oxide to enable precise observation of the surface and improve the image quality.

Assessment of porosity with the use of microscopic and submicroscopic studies

Light microscopic studies

Figure 3 presents structural studies using a light microscope.

From the microstructural analysis (Figure 3), it can be concluded that the reinforcing particles accumulate around the edge of the pore (Figure 3a). In the case of incomplete and insufficient filling of the reinforcing spaces between the particles of the reinforcing phase, gaps and gas voids can be observed (Figure 3b).

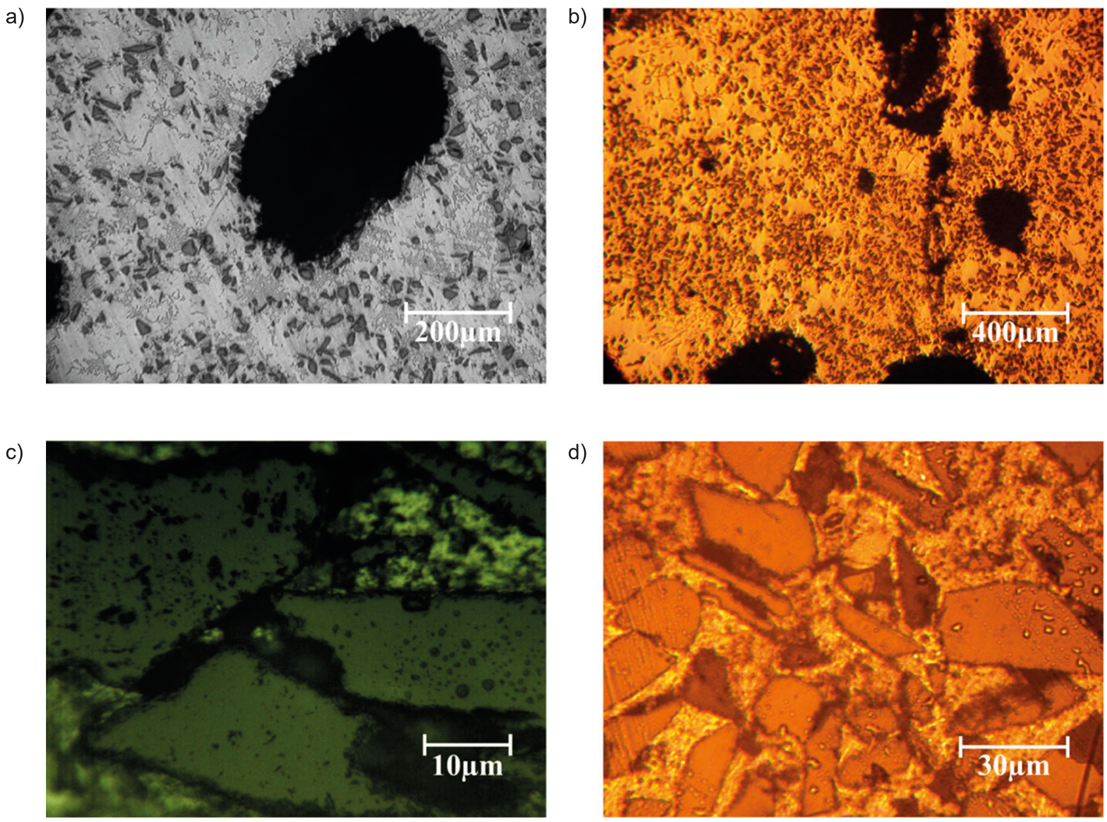

Figure 3. Composite microstructures: a), b) secondary agglomerates (suspension composites); c), d) leaving the reinforcement space not filled (infiltration composites). Light microscopy images

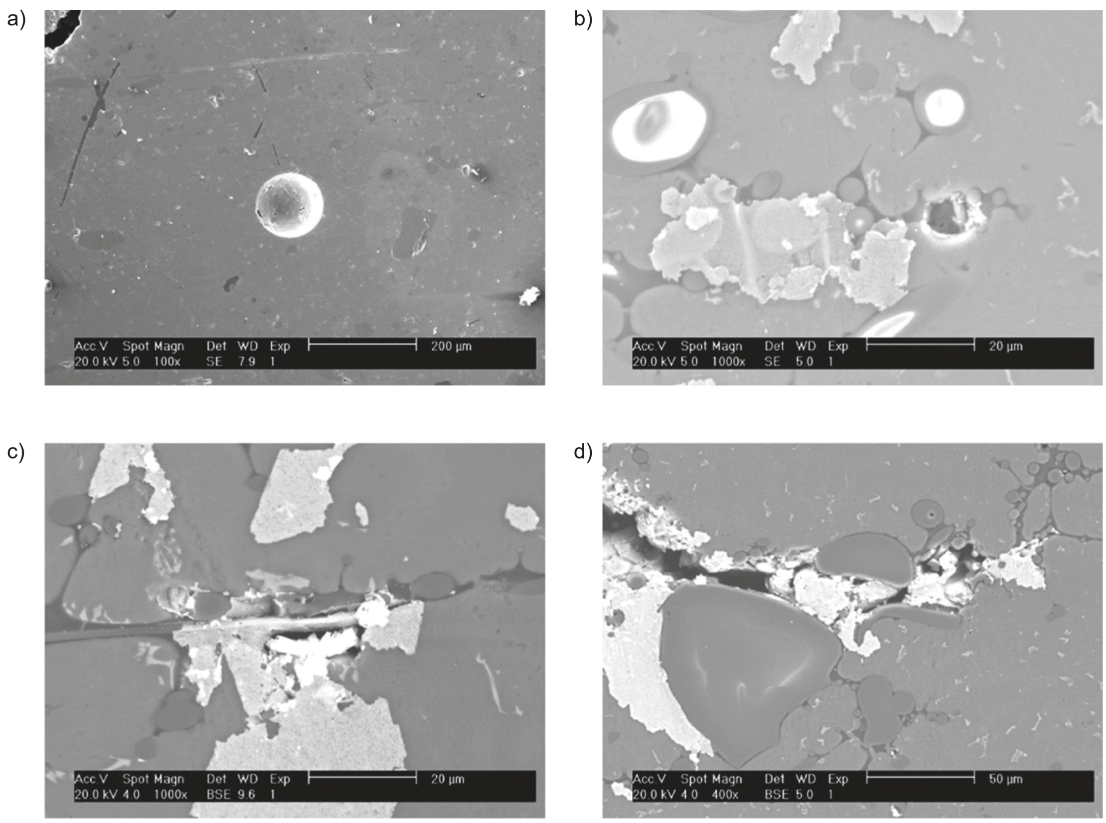

Figure 4. Submicrostructures of composites: a) occluded bubbles (suspension composites), b) isolated gas bubbles (suspension composites); c), d) leaving the reinforcement space not filled (infiltration composites). Scanning electron microscopy images

Scanning electron microscopic studies

Figure 4 presents structural studies with the use of a scanning electron microscope.

It can be concluded from the submicrostructural analysis (Figure 4) that the gas bubbles take a spherical shape located in the reinforcement space (Figures 4a and 4b). There are also visible empty spaces in the composite structure with clearly visible reinforcement elements (Figure 4c)

Conclusions

In this study on the assessment of porosity in suspended and infiltration metal composite materials, the combination of microscopic and submicroscopic methods is accurate. These methods can be successfully used to assess porosity in metal composites. Specific defects belonging to the porosity group were distinguished and are listed below:

- Non-filling of the reinforcement space characterized by free spaces at the contact of reinforcement elements
- Primary and secondary agglomerates, which are breaks in the continuity of the structure with elements of the reinforcing phase located at the edge of the pore
- Occluded bubbles characterized by pores of an almost spherical shape, occurring in the entire volume of the casting with dimensions increasing in its isolated areas
- Separated gas bubbles are characterized by gas pores of regular spherical shape

Assessment of this specific defect with the use of the applied tests will contribute to the improvement of the quality of finished products, cast composite combustion pistons.

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