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Image processing-based analysis of interfacial phases in brazed stainless steel with Ni-based filler metal

Dong Yong Park[a], Sun Kyu Lee[b], Jong Kyu Kim[a], Sang Nam Lee[a], Seong Jin Park[c], Yong Jun Oh[b,*]

[a] Solar Thermal Convergence Laboratory, Korea Institute of Energy Research, 152, Gajeong-ro, Yuseong-gu, Daejeon 34129, South Korea
[b] Division of Advanced Materials Engineering, Hanbat National University, 125, Dongseo-daero, Daejeon 34158, South Korea
[c] Department of Mechanical Engineering, Pohang University of Science and Engineering (POSTECH), 77, Cheongam-Ro, Nam-Gu, Pohang, Kyeongbuk 37673, South Korea

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ABSTRACT

This work presents an image processing method to identify the distribution of Cr_xB_y in a brazed joint of SUS304/MBF20/SUS304. Although the chemical compositions at designated locations on such joints can be measured through electron-probe microanalysis (EPMA) and transmission electron microscopy (TEM), determining the overall distribution of Cr_xB_y and quantitatively describing this phase is difficult. Therefore, an image-processing algorithm was developed using material-specific intensity differences in backscattered electron images. The image-processing algorithm was verified and validated by EPMA and TEM measurements. Based on the developed image processing method, the effects of the brazing temperature on the Cr_xB_y layer thickness were quantitatively analyzed.

1. Introduction

Brazing as a joining process is widely employed in industrial applications [1]. Stainless steel brazed with a rapidly solidified high-mechanical-strength Ni-based filler metal containing B as a melting-point depressant is a particularly promising material candidate [2–6]. Although interfacial wettability induced by B diffusion can enhance the joining capacity in brazing [7,8], brittle and hard phases induced by combining B and Cr can reduce the joining strength. Thus, the mechanical properties, including tensile and fatigue strengths, of microstructures related to brittle phases have been evaluated. Rabinkin [5], for example, discussed the relationship between microstructure and strength, concluding that the CrB phase degraded the mechanical strength of steel with a Ni-based filler metal. Many have studied the avoidance or reduction of intermetallic phase formation by reducing the B content or adjusting the processing conditions, including the heating rate, holding time, temperature, and width of filler metal. B-free filler metals, such as Au–Ni, Au–Ni–Cr, Ag–Pd, Ag–Cu–Pd, and Cu–Mn–Ni, have been employed to prevent the formation of brittle silicide and boride phases [9–12]. However, Ni-based filler metals containing B, such as the MBF series, are widely used for economic reasons. Therefore, optimizing the processing conditions for brazing to reduce the formation of detrimental phases such as Cr_xB_y has been investigated. Rabinkin et al. [2,5,13,14] reported the characteristics of various filler metals, including MBF-series alloys. They investigated the microstructural evolution of intermetallic boride phases and the mechanical properties upon changing the processing conditions. Furthermore, they provided guidelines for optimized brazing conditions for various brazing filler metals and base metals. Lugscheider and Partz [3] investigated the influence of brazing time, temperature, clearance, and heat treatment for 316 stainless steel with Ni-based filler metals, including BNi-2, BNi-5, and BNi-7. They evaluated the maximum brazing clearance, i.e., the maximum brazed joint clearance without brittle intermetallic phase formation, in wedge gap specimens; the formation of brittle intermetallics was affected by the brazing conditions when B-containing BNi-2 and BNi-5 were used. Jang and Shin [15] evaluated the microstructural evolution and shear strength of 304 stainless steel with a Ni-based filler paste containing varying Si levels. They found that increased Si contents were required at higher brazing temperatures because of the increased liquidus temperature, while the formation of different phases, including Ni solid solutions, Ni_3Si, Ni_3B, and CrB depended on the Si contents. Jiang et al. [16] investigated the effects of brazing temperature; brittle phases were always observed regardless of changes in brazing temperatures, but increased brazing temperatures promoted the uniform distribution of brittle boride compounds. High brazing temperatures thus correlated to increased tensile strength. Lemus-Ruiz et al. [17] presented the effects of different brazing temperatures and times on the shear strength and corrosion resistance; these parameters triggered thermally activated atomic diffusion, affecting the shear strength. Roy et al. [9] evaluated brazed joints using

* Corresponding author.
E-mail address: yjoh@hanbat.ac.kr (Y.J. Oh).

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Cu-based and Ni-based filler metals, examining the microstructure and bonding strength of the joint regions. Philips et al. [10] performed analytical modeling and experimentally investigated the kinetics of dissolution and isothermal solidification to understand the joining mechanism. Others analyzed the effects of brazing temperature and joining thickness [18]. Finally, microstructural analyses of intermetallic phases were reported by several groups [19,20], who observed the formation of Cr_xB_y phases at the interface of ferrous material and B-containing Ni-based filler metal through backscattered electron (BSE) images and electron-probe microanalysis (EPMA) mapping.

Although many researchers have performed microstructural analysis of intermetallic phases such as Cr_xB_y and their mechanical characteristics, most of them have focused on the observation of chemical compositions related to Cr_xB_y at specific locations through methods such as field-emission scanning electron microscopy (FE-SEM), EPMA, or transmission electron microscopy (TEM). While X-ray diffraction (XRD) analysis can determine the formation of Cr_xB_y phases, the latter are quantitatively measured at designated areas only, without regard for their distribution elsewhere. Therefore, distribution analysis methods would be useful to intuitively distinguish various Cr_xB_y distributions at the joint interface and understand the microstructural evaluation. Therefore, in this study, a straightforward image-processing method was developed to detect the distribution of Cr_xB_y at brazed joints; the effects of brazing temperature were quantitatively analyzed through the developed method.

2. Conceptual Background of Image Processing for Cr_xB_y Phase Identification

The image processing algorithm to distinguish Cr_xB_y from other phases is based on intensity differences in BSE images. Considering several previous studies related to the microstructure of the Cr_xB_y phase [2,5,18], the Cr_xB_y phase is represented by a dark color, i.e., the Cr_xB_y phase has a lower intensity than other phases. Therefore, dark areas can be confirmed as Cr_xB_y phases, and their distribution can be identified by image processing using BSE images. Fig. 1 shows each step of the developed image processing routine. After brazing, the interface of the brazed joint is measured by SEM to obtain a BSE image. In this BSE image, the Cr_xB_y phase can be distinguished from various other phases using intensity differences. Even though we already know that the Cr_xB_y phase has a low intensity, this fact should be experimentally verified. To confirm the results of the developed image processing method, the chemical compositions of interfacial phases should be measured by EPMA mapping. Among all detected chemical compositions, the individual distributions of Cr and B are then extracted to estimate the distribution of the Cr_xB_y phase. The distribution of the Cr_xB_y phase can be estimated from overlapping areas in the individual data for Cr and B. Therefore, if the extracted areas based on the intensity differences in the BSE image can be successfully matched with the overlapping areas of individual Cr and B contributions in EPMA mapping, the developed image processing method can be considered valid. In addition, the presence of the Cr_xB_y phase should be experimentally confirmed using direct measurements by TEM. If the extracted low-intensity area has a similar chemical composition and ratio of B and Cr as in the identified Cr_xB_y phase, it can be concluded that the developed image processing algorithm gives reliable results.

The developed image processing method allows quantitative analysis of the distribution of the Cr_xB_y phase under different processing conditions. The numerical process applied to identify the width of the Cr_xB_y phase is as follows: i) the distribution of the Cr_xB_y phase is extracted from intensity differences in the BSE image; ii) the intensities assigned to the Cr_xB_y phase are summed up along the x-direction, i.e., parallel to the joint direction; iii) finally, the width of the Cr_xB_y phase is defined as 25% of the maximum intensity of the summation of the intensities parallel to the joint direction. Considering the image processing results at various brazing temperatures, the value of 25% of the maximum intensity was empirically determined, as it allowed optimal intuitive distinction of the Cr_xB_y phase from other phases.

3. Experimental Procedures

A base metal plate of SUS304 and a Ni-based amorphous-structured foil MBF20 (produced by Metglas Inc., USA) as filler metal were used. The thicknesses of SUS304 and MBF20 were 2 mm and 50 μm, respectively. The compositions of both materials are summarized in Table 1.

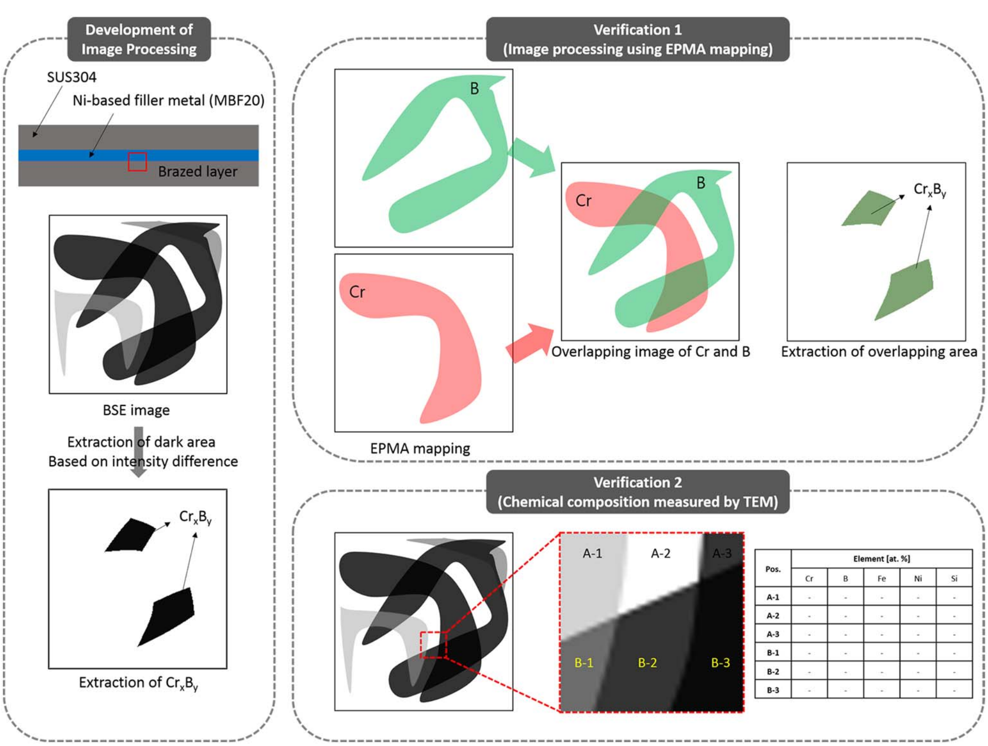

Fig. 1. Schematics of the developed image processing method and verification processes for the identification of the Cr_xB_y phase.