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# Micro flash butt welding of super duplex stainless steel with Zr-based metallic glass insert

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A B S T R A C T

Micro flash butt welding of super duplex stainless steel with Zr-based metallic glass insert was carried out. $Zr_{55}Cu_{30}Ni_5Al_{10}$ of Zr-based metallic glass with thickness of 50 μm and Zr metal with thickness of 500 μm were used as the insert materials. After welding, Zr-based metallic glass insert became much thinner than that of Zr metal insert. The supercooled liquid of Zr-based metallic glass insert at the interface was protruded outside of the specimen during welding. The formation of the protrusion discharged the oxide films on the butting surfaces and contact surface, resulting in metallurgical bonding through the fresh surfaces. The Fe–Zr metallic compounds were observed at the bonding interface for the Zr metal insert, but the metallic compound for Zr-based metallic glass insert was hardly observed. The micro flash butt welding of stainless steel with Zr-based metallic glass insert was successfully welded.


## 1. Introduction

Duplex stainless steels are consisting of ferrite–austenitic microstructure and exhibit greater toughness and better weldability than those of ferritic stainless steels [1]. They have higher strength and better corrosion resistance than austenitic stainless steels [2]. Their good engineering performance has led to an increasing number of applications, mainly in corrosive environments such as sour gas pipelines and chemical reaction vessels. As the welds were heated above 1573 K during GTA welding, the phase balance of ferrite and austenite was varied significantly and the toughness was much lower than that of the base metal [3,4].

In order to improve the weldability, micro flash butt welding with insert materials such as Zr metal and Zr-based metallic glass will be needed. Zr metal and Zr-based metallic glasses are superior to corrosion than that of the super duplex stainless steel.

The metallic glasses have many potential applications due to their unique properties, such as superior strength and excellent corrosion resistance. Zr–Cu–Ni–Al metallic glass has high glass formability and wide supercooled liquid region [5]. But if the heating rate and cooling rate during heat treatment were slow, metallic glasses were crystallized and the superior properties were disappeared. There are only a few reports on the joining of metallic glasses by laser welding [6] and the friction bonding [7]. However, there is no report by the micro flash butt welding, because of the difficulty of the temperature controlling at the butting surface.

In this study, the joining of the super duplex stainless steel with Zr metal insert and Zr-based metallic glass insert was carried out by the micro flash butt welding with the temperature controlling system.

## 2. Experimental procedure

The base metal was a super duplex stainless steel (329J4L) with chemical composition (mass%) of 25%Cr–7%Ni–3%Mo–0.2%N. The specimens were cut out from the base material plate with 12 μm thickness along rolling direction. The specimens were mounted in the dies using a Gleeble thermal simulator and the flash butt welding was made. $Zr_{55}Cu_{30}Ni_5Al_{10}$ of 50 μm in thickness as Zr-based metallic glass and Zr metal of 500 μm in thickness were used as the insert materials. The glass transition temperature ($T_g$) and crystallization temperature ($T_x$) of $Zr_{55}Cu_{30}Ni_5Al_{10}$ are 683 K and 767 K, respectively [8].

Fig. 1 indicates a schematic illustration of the flash butt welding using a Gleeble simulator. The specimens were fixed. The weld thermal cycles at the butting surface of the specimen was controlled at 1373 K by the attached thermocouple. The specimens were heated up to 1373 K for 30 s under the pressure of 10 MPa.

For welding, specimens were mounted, aligned and clamped in the dies. The ends of the insert materials and stainless steel contacted each other under the constraint pressure. When the current was turned on, heating begun. This heating consists of bringing the ends of the materials together and separating them several times in succession, each time causing a short circuit. The insert materials were heated during this passage of current, particularly at the butting surfaces. As the current passed through the specimen,

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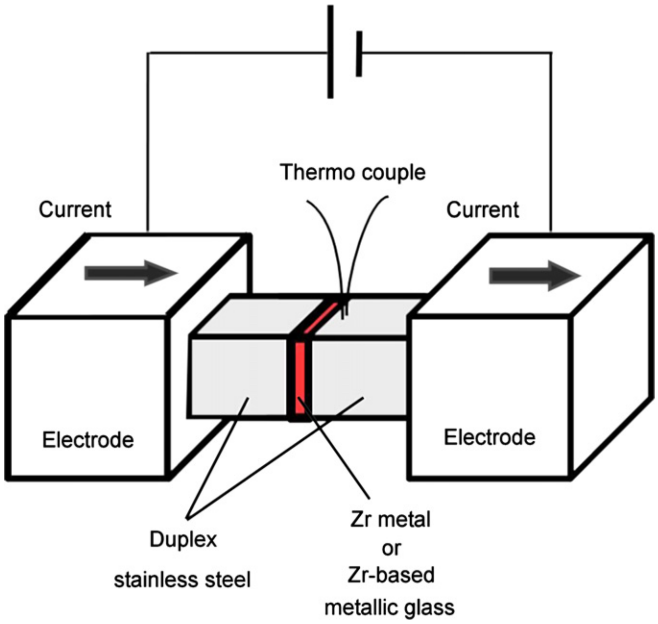


**Fig. 1.** Schematic illustration of resistance welding apparatus.

intense localized heating occurred between the contact faces. During the flashing period, the heat generated was intensified by the inadequate contact between the faces to be welded, which rapidly brought the flashing surfaces to a high temperature. On both sides of the flashing surfaces the temperature falls rapidly off, resulting in a narrow heated zone.

The welded specimens were examined by an optical microscopy, a scanning electron microscopy (SEM), and an energy dispersive X-ray spectroscopy (EDX). Intermetallic compounds were identified by X-ray diffraction technique using Cu radiation. Charpy impact test was carried out at room temperature after welding. The fracture surfaces were observed using scanning electron microscopy.

## 3. Results and discussion

Fig. 2 shows the temperature–time curve during the flash butt welding for super duplex stainless steel (329J4L) with Zr-based metallic glass insert. The temperature curve indicates the fluctuation, and extremely fluctuated at 683 K, 1100 K and 1373 K [9], because of the superplasticity at the supercooled liquid state, the

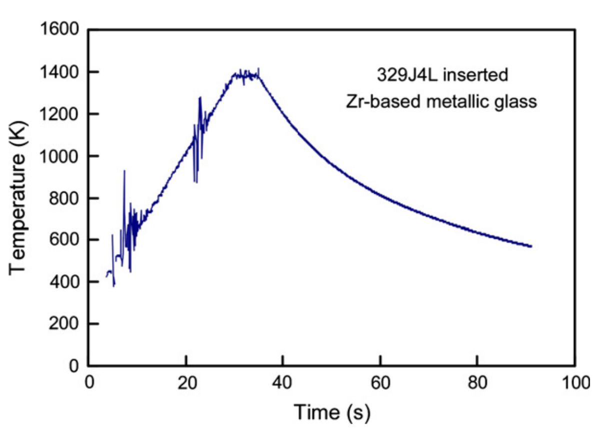


**Fig. 2.** Thermal cycle of resistance welding at 1373 K for super duplex stainless steel with Zr-based metallic glass insert.

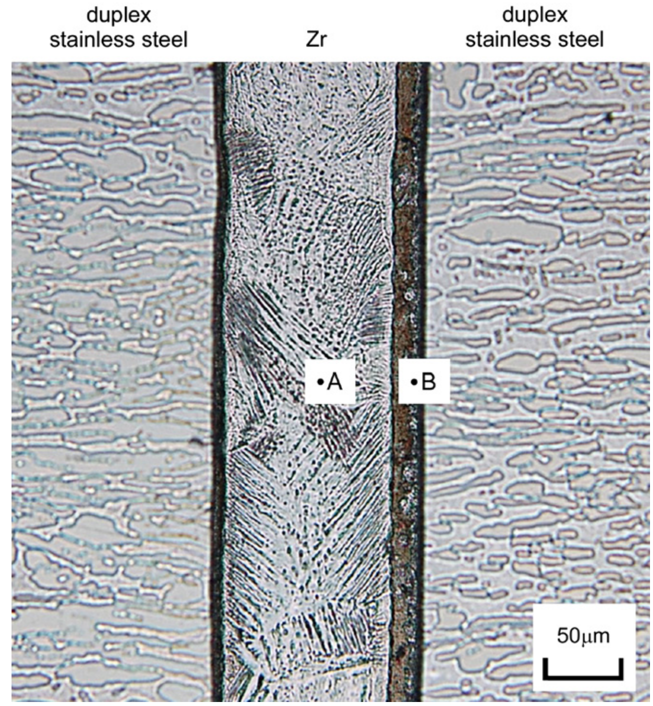


**Fig. 3.** Optical microstructures of the bonding interface with Zr metal of 0.5 μm in thickness insert.

liquid state of Zr-based metallic glasses at the melting point, and the liquid state by eutectic of Ferrous and Zr metal, respectively.

As the samples without joining was heated, the temperature–time curves during the heating process were almost linear and hardly showed fluctuation such as a zigzag phenomena [6]. Consequently, the fluctuation suggests that flashing action took place [6], and no electrical interference occurred.

On the basis of the continuous cooling transformation (CCT) curves from a supercooled liquid to the amorphous or crystalline phase for $Zr_{55}Cu_{30}Ni_5Al_{10}$ and CCT curve of $Zr_{55}Al_{10}Ni_{10}Cu_{25}$ [10,11], the cooling rate shown in Fig. 2 is faster and the cooling time was shorter than the nose-point of CCT curve of $Zr_{55}Al_{10}Ni_{10}Cu_{25}$. Consequently, it is considered that the Zr-based metallic glass was almost amorphous after welding.

Fig. 3 shows the cross-sectional microstructure of the bonding interface for the specimen with Zr metal insert after flash butt welding. Elongated white region in the super duplex steel shows austenite phase, and gray region in the super duplex steel shows ferrite phase. Ferrite grain growth of the steel is hardly observed [3]. The inserted Zr metal indicated Widmanstatten alpha microstructure, and the point analysis at mark A indicated only Zr peak as shown in Fig. 4A.

The intermetallic compound of 2 μm in thickness is observed as a narrow layer of the dark contrast with uniform thickness between the super duplex stainless steel and the Zr metal as shown in Fig. 3. According to the X-ray diffraction results, $ZrCr_2$ and Zr–Fe of the intermetallic compounds were detected as shown in Fig. 4B. The result is similar to a report of the hot pressure bonding result between AISI 304L and Zircaloy-2.

The Vickers hardness was measured. As per the results, the hardness of the duplex stainless steel was Hv350, the hardness of the Zr insert metal was Hv200, and the hardness of the intermetallic compounds was Hv500. The fracture is expected to occur at the intermetallic compounds for Charpy impact test. When Zr metal was heated above 1143 K, alpha phase (alpha-Zr) was transformed to beta phase (beta-Zr), and then beta phase (beta-Zr) was transformed to alpha-Zr phase by rapid cooling (Fig. 3).