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Effectiveness of electrically assisted solid-state pressure joining using an additive manufactured porous interlayer

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ABSTRACT

A solid-state pressure joining using resistance heating as a heat source and adopting an additive manufactured metal porous interlayer between joining specimens is demonstrated. During the joining of 316L stainless steel cylindrical specimens, an electric current is directly applied to the joint under continuous axial compression. Defect-free joints are successfully fabricated with a lower joining pressure when applying the porous interlayer with a lower compressive strength and higher electric resistivity. The microstructural analysis confirms that the porosity is eliminated as a result of the compressive deformation during joining, and recrystallization takes place in the interlayer.

1. Introduction

In the manufacture of metallic structural components, joining is an inevitable process due to the limited formability of metal alloys. In the joining of metallic components, fusion joining of metals is commonly employed. However, with increasing use of dissimilar or difficult-to-weld metal alloys, the number of occasions in which conventional fusion joining is not applicable has been increasing in various industries.

Solid-state joining processes, which are metallurgical joining processes by plastic deformation [1], have been considered as alternatives for conventional fusion joining processes. Solid-state joining processes such as pressure joining [2,3] and friction welding [4,5] generally generate joints by establishing diffusion bonding between metal surfaces under pressure. In pressure joining, metals are compressed against each other and deformed. Due to the compressive deformation of metals, the oxide layers break and virgin metals make contact with each other [2,3]. As a result, a solid-state joint is generated without the formation of a liquid phase. Pressure joining generally needs to be conducted at elevated temperatures. Therefore, in a conventional hot pressure joining process, complex heating and control facilities are generally required. Also, the acceptable size of any part involved in this process is limited to the size of the furnace.

Friction welding also uses the same bonding mechanism of pressure joining and is usually considered for joining cylindrical parts. This produces solid-state joints of metals by the frictional heat obtained from a mechanically induced relative sliding motion (in general, by rotation) between the surfaces of two workpieces in contact under pressure [4,5]. An advantage of friction welding is that operating temperatures are significantly lower than those of conventional fusion joining [6]. However, friction welding requires a relatively expensive and complex brake system since the rotation of a workpiece must be stopped completely and rapidly for successful joining [4]. Note that no additional frictional heat is generated during the actual generation of a solid-state joint since the rotation ceases prior to the final axial compression during friction welding. Also, a large amount of flash is exhausted from the joint interface by the final axial compression during friction welding and thus must be removed after the process.

To overcome or minimize the drawbacks of conventional pressure joining and friction welding, electrically assisted pressure joining (EAPJ) using resistance heating as a heat source is a possibility [7,8]. EAPJ is a solid state joining without melting in contrast to the resistance spot welding, which generally involves melting and solidification. In comparison to conventional pressure joining, using resistance heating as a heat source provides several technical advantages. First, the workpieces can be heated rapidly and locally. As a result, the process time can be reduced and unnecessary thermal effects on the workpiece can be minimized. Also, the joining apparatus can be significantly simpler and cost-effective, as the need for a heating furnace can be eliminated. EAPJ of metal sheets or foils has been successfully demonstrated by several researchers. For example, Ng et al. [9] conducted electrically assisted roll bonding of aluminum/aluminum and aluminum/copper sheet combinations. Xu et al. [10] also joined stainless steel 316L foils by EAPJ.

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The concept of EAPJ also provides technical advantages over friction welding in the joining of bulk workpieces. By using resistance heating as a heat source, the need for complex rotation and brake systems can be eliminated. Also, since the heating of the interface can be continued during the final axial compression, process optimization is relatively easier. In the present study, improvement of the process effectiveness for the EAPJ of cylindrical bulk components is demonstrated by using an additive manufactured metal porous interlayer.

2. Experimental set-up

For EAPJ of bulk specimens, solid cylindrical specimens with a diameter of 10 mm were machined using a commercial stainless steel 316L alloy (SUS 316L). Solid cylindrical specimens with a height of 15 mm were machined for EAPJ without a metal porous interlayer, while solid cylindrical specimens with a height of 13 mm were machined for EAPJ with a metal porous interlayer. The metal porous interlayers with a diameter of 10 mm and a height of 4 mm were fabricated using SUS 316L powder (Sandvik Osprey, UK) by metal additive manufacturing (or simply, metal 3D printing) with selective laser melting. The particle size of the SUS 316L powder used is in the range of 15–45 μm. A commercial metal 3D printer (MetalSys 150, Winforsys, South Korea) with a laser spot size of 40 μm was used to fabricate the metal porous interlayers. The interlayers were fabricated to have two different porosities of 8 and 12 vol.% (based on the relative density) by adjusting the laser power and scan speed of the additive manufacturing process, as shown in Fig. 1(a). Also, cylindrical porous specimens (8 and 12 vol.% porosities) with a diameter of 10 mm and a height of 15 mm were fabricated to measure the baseline compressive properties. Baseline compression tests were conducted with a displacement rate of 24 mm/min at room temperature. Three different assemblies of solid specimens and a porous interlayer were evaluated, as described in Fig. 1(b). The three different assemblies are identified as S + S, S/3D8%, and S/3D12%. All the specimens were thoroughly cleaned by acetone prior to the experiments.

A custom-made fixture was installed in a universal testing machine (DTU900-MH, Daekyoung, South Korea) for EAPJ, as described in Fig. 2(a). The resistance heating during compression for joining was induced by a programmable electric current generator (Vadal SP-1000U, Hyosung, South Korea). Upper and lower dies made of tool steel for compression were also used as electrodes. A set of insulators made of bakelite was inserted between the die and the machine to isolate electric current from the testing equipment.

During EAPJ, axial compression and an electric current were simultaneously applied to the specimen assembly (Fig. 2(b)). A constant displacement rate of 24 mm/min and a maximum displacement of 6 mm were used for all EAPJ experiments. As described in Fig. 2(b) and listed in Table 1, for resistance heating during compression, a continuous electric current was initially applied to the specimen assembly to rapidly increase the temperature. Then, a pulsed electric current was applied to the specimen assembly to accelerate atomic diffusion by maintaining an elevated temperature without overheating. To verify the repeatability of the results, the experiments were conducted at least three times for each specimen assembly. In the experiment, the load history was recorded as a function of displacement. The temperature of specimen assembly during joining was also continuously recorded using an infrared thermal imaging camera (FLIR-T621, FLIR, Sweden).

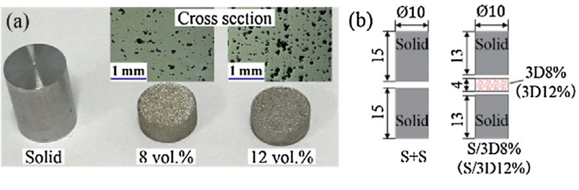

Fig. 1. (a) Solid specimen and metal porous interlayers with 8 and 12 vol.% porosities, and (b) schematics of specimen assemblies.

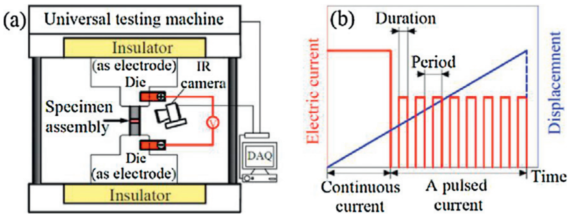

Fig. 2. Schematics of (a) the experimental set-up and (b) electric current during compression.

Table 1
Electric current parameters of joining experiments.

Step	Nominal current density (A/mm^2)	Current duration (s)	Pulse period (s)	Total time (s)
Continuous current	32	5	–	5
A pulsed current	19	0.75	1.25	10

For the microstructural analysis, the cross section of the joint was prepared along the joining direction. The cross-sectional sample was first examined by optical microscopy (OM) after etching using 50 ml of hydrochloric acid with 15 g of iron(III) chloride to confirm that the joint was fabricated without macroscopic defects. The microstructure of the joint was further observed using a field emission gun scanning electron microscope (FE-SEM, SU70, Hitachi, Japan) equipped with an electron backscatter diffraction system (EBSD, EDAX/TSL, Hikari, USA). The mechanical properties of the joint were evaluated by Vickers hardness measurements (9.8 N, 10 s) of the cross section along the center line in the joining direction using a Vickers indenter (HM-100, Mitutoyo, Japan). Finally, to confirm a sufficient joint strength, the joints were machined to cylinders with a diameter of 8 mm and simple cantilever bend tests were conducted.

3. Results and discussion

The results of the baseline compression tests (Fig. 3) clearly show that the elastic modulus, compressive yield stress, and compressive flow stress of the cylindrical porous specimens fabricated by the additive manufacturing process are lower than those of the solid cylindrical specimen. Note that the load-displacement curve is used instead of the stress-strain curve due to barreling during compression.

Using the well-known Gibson–Ashby model [11], the relationship between the relative yield strength and relative density can be described to obey a power law relationship as,

$$\frac{\sigma_p}{\sigma_s} = 0.90\left(\frac{\rho_p}{\rho_s}\right)^{4.02} \quad (1)$$

where σ and ρ represent the 0.2% compressive yield stress based on the original cross-sectional area and the bulk density,

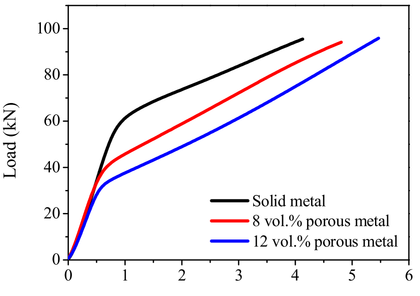

Fig. 3. Load–displacement curves from the baseline compression tests.

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