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Effect of surface pre-oxidation on laser assisted joining of acrylonitrile butadiene styrene (ABS) and zinc-coated steel

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ABSTRACT

Surface oxidation pre-treatment of zinc-coated steel was performed to verify its effect on enhancing the joint strength in the laser assisted joining of acrylonitrile butadiene styrene (ABS) and zinc-coated steel. Tensile shear tests indicated that the joint strength between pre-oxidized zinc-coated steel and ABS was considerably enhanced in comparison with that of untreated joint. The zinc oxide layer was generated in the zinc layer by pre-treatment on zinc-coated steel and the thickness of the zinc oxide layer is proportional to the joint strength of joining as long as the strength of zinc oxide layer is higher than that of the jointed layer. When the thicker zinc oxide layer on the zinc-coated steel is reacted with carbon on the ABS, it increases the potential for chemical bonding between the zinc oxide and carbon (Zn–O–C). Using scanning electron microscopy (SEM) and coupled with energy dispersive X-ray spectroscopy (EDS) and X-ray photoelectron spectroscopy (XPS) measurements, the strongly jointed areas were evaluated at atomic or molecular levels to investigate the physical and chemical bonding between the reacted carbon layer and zinc oxide layer.

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1. Introduction

Over the last decade, electro galvanized iron (EGI) as one of the zinc-coated steel has become widely used in the automobile industry to concerns about higher energy costs and more stringent environment regulations, and the desire for green manufacturing. EGI has excellent corrosion resistance, good paintability, formability and weldability, and improves the durability of the vehicle body [1–3]. At the same time, increasing demands for reductions in weight to enhance fuel economy have impacted the steel dominated content of automobiles. Manufacturers now utilize a greater proportion of polymer materials because of their low density and excellent mechanical properties [4–7]. With the increasing use of both EGI and polymers, various technologies have been developed to join these two materials based on conventional joining methods for dissimilar materials, such as adhesive bonding and mechanical fasteners (bolts and rivets) [8]. However, these conventional methods have several problems, including the need for additional pre- and post-processing, and inconvenient mass production. As a result, new joining technologies have been developed recently, such as instance friction spot bonding, ultrasonic bonding, and laser assisted joining. Among these, laser assisted joining is appropriate for mass production because it is fast, simple and flexible, able to access structures of any shape.

Research into the laser assisted metal and polymer (LAMP) joining was carried out by Katayama et al. [9], and developed by Jung and Kawahito [10–12] as a rapid and strong process for joining dissimilar commercially available metals and polymers. These studies reported that LAMP joining was a result of the interaction between high vapor pressure caused by the rapid expansion of bubbles generated in the melted polymer near the joint interface, and a flexible flow of liquid phase polymer pushed to the metal surface. The joint strength with around 3000–4000 N could be produced [9–12]. Further research revealed and clarified the bonding mechanism of LAMP joining, to include physical, chemical and mechanical bonding processes as well [13–15]. Tillmann et al. [16] performed laser assisted joining between stainless steel (SUS304) and polyethylene terephthalate glycol modified (PETG) to attain suitable joint strengths with two important process parameters such as laser power and scan speed. As a result, increasing the laser power and decreasing the scan speed has shown to increase the joint strength to an optimum level. In contrast, the excessive heat input more than the optimum level leads to a low joint strength by excessive pore formation. Fortunato et al. [17] experimentally evaluated the feasibility of joining processes between metal and various plastic components by means of the exploitation of a laser source. Cheon et al. [18] evaluated the quantitative relationship among joint strength, the expansion pressure, gas fragment composition, and molecular structure based on the experiments and simple chemical analysis. As a result, expansion pressure of pyrolysis fragments of the polymer increases with a decreasing monomer yield, which is determined by the molecular structure of the polymer [18]. Arai et al. [19] investigated the effect of

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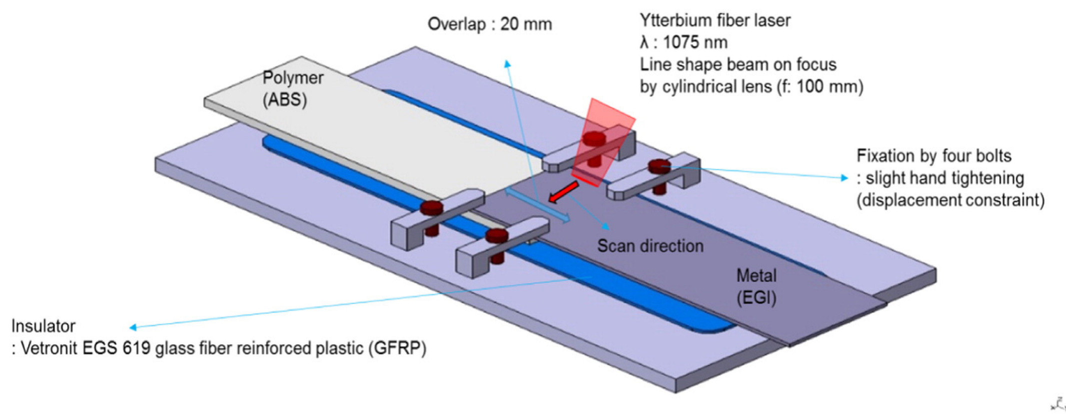

Fig. 1. Schematic of the experimental setup of the laser assisted metal and polymer joining, using a line shape beam via a cylindrical lens. The specimens are fixed by four bolts with slight hand tightening (displacement constraint).

surface pretreatment of cyclic olefin polymer (COP) and SUS304 on the strength of a laser joint between these two materials. By applying the surface modification to COP and SUS304, laser joint strength was considerably increased to over 8 MPa (6400 N with overlapped area 800 mm^2) [19]. Yusof et al. [20] investigated the effect of anodizing on the shear strength of dissimilar materials joint between PET (polymer) and A5052 (aluminum alloy). The PET/A5052 (anodized) joint showed 36% higher shear strength compared to the PET/A5052 (as-received) joint [20]. Roesner et al. [21] have achieved progressive enhancements of joint strength between metal and polymer by employing laser micro grooving on the metal surface. As a result, they observed a minor improvement in the joint strength (15 MPa, 1500 N with overlapped area 100 mm^2) of polyamide 6.6 after this surface pretreatment, which produced mechanical interlocking of the joint [21]. They found that a strong LAMP joint could be produced by chemical (ionic bonding) and physical bonding (Van der Waals forces) on the atomic or molecular sized level between a melted base plastic and an oxide film existing on the metal surface, as well as mechanical bonding (anchor effect) related to surface roughness of a metal [9–15]. However, so far efforts to enhance LAMP joint strength by pre-oxidation process in metal to improve the chemical bonding near the joint interface have not been carried out. Chemical bonding produces a much stronger bonding force than other bondings such as physical and mechanical bonding.

In this paper, therefore, in order to enhance the joint strength between EGI and ABS by LAMP joining, an intentional pre-oxidation process was performed on the surface of the EGI using a selected temperature and air atmosphere in a furnace, based on the following hypothesis. It was thought that reacting a thick zinc oxide layer on the EGI with the carbon on the ABS would increase the possibility of chemical bonding between the zinc oxide and carbon (ZnC). In order to characterize the materials interaction between bare EGI and ABS, process parameters such as scan speed and laser power were optimized in LAMP joining. And then, LAMP joining between pre-oxidized EGI and ABS was carried out with these process parameters to verify the effect of pre-oxidation of EGI on joint strength. In addition, the characteristics of heat absorption from laser irradiation and heat transfer in each EGI specimen were evaluated by several experiments. The relation between joint strength and fractured surface of LAMP joint after tensile shear test was also examined. Finally, the strongly jointed areas were further analyzed on atomic and molecular levels using SEM/EDS and XPS measurements, to investigate the physical and chemical bonding between the reacted carbon layer on ABS and the zinc oxide layer on the surface of EGI.

2. Experimental

ABS (AB303300, GoodFellow Corporation) was selected as the polymer material in this research, since it is widely used in industry due to its superior mechanical properties, chemical resistance, ease of processing and recyclability [7]. As the metal material, commercially available electro galvanized iron (EGI) was chosen. ABS is white and opaque with 3 mm thickness and EGI is light gray metal with 1.2 mm thickness. All specimens used in the LAMP joining were prepared to be 25 mm in width and 100 mm in length.

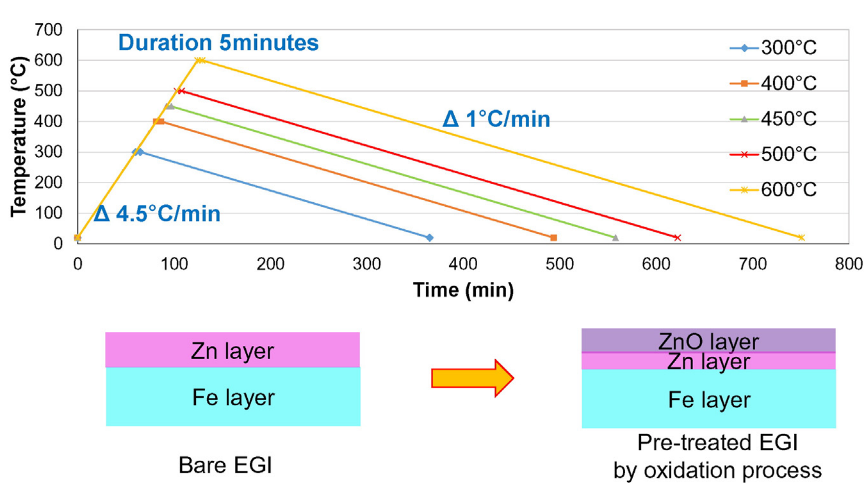

Fig. 2. Temperature profile for the oxidation process and schematic illustration of cross section of oxidation process.

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