博士論文（要約）

Joining using plastic deformation for thin sheets of dissimilar metals and metal sheet with FRP sheet

（異種金属薄板とFRP薄板−金属薄板の
塑性変形を利用した接合プロセスに関する研究）

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In recent decades, the pursuit of reducing energy consumption and CO_2 emission has been stimulating the relevant industries to develop more and more ultra-lightweight constructions with high productivity. Aluminum alloy and thermosetting fiber-reinforced plastic (FRP) have been used extensively to replace low carbon steels for manufacturing primary and secondary products in aircraft and automotive industrial fields. However, the full exploitation of the application potential of the lightweight hybrid structures is restricted by the development of excellent dissimilar joining technologies.

The requirement of further reducing the thicknesses of the components for fabricating ultra-lightweight hybrid structures makes the aluminum alloy-to-steel and thermosetting FRP-to-metal dissimilar joining become more challenging issues. Because for ultra-thin sections, the conventional dissimilar joining techniques, such as the mechanical fastening, mechanical clinching, thermal welding, friction stir welding, become less effective or even inapplicable. From both scientific and industrial viewpoints, to realize more and more practical applications of ultra-lightweight hybrid structures, it is of high necessity to explore more reliable, high-quality and economic dissimilar joining methods for aluminum-to-steel and metal-to-thermosetting FRP dissimilar combinations involving ultra-thin joining section (less than 1 mm in thickness).

This doctoral dissertation aims at overcoming the technical challenges by proposing more effective joining processes achieved or assisted by plastic deformation (similar as die forging in air). The sticking point in this research is effectively improving the formability of the lightweight materials, reducing the amount of springback of the composite material with high specific strength and stiffness as well as increasing the forming consistency between the dissimilar joining sections during plastic deformation. Applying induction heating and accurate controlling of forming stroke were utilized as solutions to increase the ductility of the metallic thin sheets and the strain-to-failure of the thermosetting FRP thin sheets. Aiming at obtaining defect-free dissimilar joints, the joining process setup and conditions were specially designed and systematically optimized. The effects of the detailed parameters of the joining process on the microstructure and mechanical properties of the base joining sections were investigated to clarify the superiorities of the proposed new dissimilar joining processes. The mechanical tests for evaluating the joining performance of the corresponding joint types included static tensile shear tests and static peel tests. The interfacial quality of the corresponding dissimilar joint was also examined at microscale by a series of metallurgical tools (*e.g.*, optical microscopy, SEM, EDS, EBSD, *etc.*). The bonding mechanisms and the contribution of the localized plastic deformation to the final dissimilar joining performance were discussed at the macroscopic, microscopic and atomic levers.

1st part: Joining aluminum alloy and stainless steel thin sheets

For 0.8-mm-thick A6061P-T6 and 0.5-mm-thick SUS304 thin sheets, a new joining process by thermally assisted plastic deformation was proposed. The effects of the forming stroke, forming temperature, heat holding time, groove width in the die as well as the radius of the punch on the dissimilar joining performance were systematically investigated. After being exposed to warm temperature as 450 ºC for 22 s, the optimal joint type was achieved by local plastic deformation using a punch-die pair in air, exhibiting the average joint efficiency factor of 85.2% and the absorption energy of 1.69 kN · mm in the tensile shear test, as well as the satisfactory performance in the peel test. No yielding gas, flux brazing or surface treatment is required. The continuous and 800-nm-thick interdiffusion layer was observed at the partial interface of the dissimilar joint, and the thickness of the interdiffusion layer at the interface was found to be positively correlated to the locally distributed plastic strain. The increase of the forming temperature has a twofold effect on the dissimilar joining performance. On one hand, a high forming temperature would effectively improve the formability of the base joining sections and accelerate atomic diffusion at the interface of the dissimilar joint. On the other hand, it would also degrade the mechanical properties of the base materials, which is detrimental for the final joining performance. The excellent joining performance of the proposed joining process were attributed to the atom-diffusion-induced chemical bonding, the microanchoring effect at the interface, the macroanchoring effect of the deformed pit and groove in the joint as well as the overall surface enlargement. It has been experimentally clarified that the proposed dissimilar joining process is an alternative joining method for Al alloy/steel lightweight hybrid structures, owing to the excellent joining performance, weight effectiveness, operation simplicity, high productivity and long tool lifetime.

In the subsequent study, the proposed dissimilar joining process by thermally assisted plastic deformation (PDX, X denotes the forming temperature) was combined with spot welding technologies. With the assistance of the resistance spot welding (RSW) or laser spot welding (LSW) process, the stability of the joining performance of all the PD350, PD400 and PD450 joint types was increased, among which the optimal one was the PD400–RSW hybrid joint type with the average joint efficiency factor of 92.4%. All the PD400–RSW hybrid joints identically exhibited the button pull-out and neck cracking co-existent failure mode. When the PD400 joint was assisted by two resistance spot welds (2RSW) which were aligned parallel to the direction of the tensile shear load, the fabricated PD400–2RSW hybrid joint type showed a remarkably increased ultimate tensile shear load compared with both the PD400 joint type and the PD400–RSW hybrid joint type. However, for the PD450 joint type, the improvement space of the tensile shear joining performance was very limited even through the additional spot weld (RSW or LSW) was applied.

The EDS line scan and EPMA mapping results revealed that several-μm-thick IMC layers were formed in the bottom regions of the hybrid joints, *i.e.*, PD400–RSW, RSW–PD400, PD400–LSW and LSW–PD400, but the interdiffusion layer thickness in the bottom region of the PD400 joint was much less than 1 μm. The relatively weak button pull-out failure mode was avoided. The enhanced interfacial bonding quality in the bottom region of the hybrid joint resulted in the higher stability of the joining performance. Moreover, the observation of the precipitation dispersion indicated that the strengthening β'' (Mg_2Si) precipitates in the neck region of the PD400–RSW hybrid joint were with relatively optimal size and homogenous distribution, while those in the PD400–LSW hybrid joint were slightly coarsened and concentrated. The increased ultimate tensile shear strength and Vickers hardness values strongly depended on the precipitation dispersion in the neck region of the corresponding hybrid joint. It has been clarified that the fusion spot weld which was introduced to the bottom region of the PD joint could further improve the ultimate tensile shear load and the reproducibility of the PD joint.

2nd part: Joining thermosetting FRP and metallic thin sheets

For joining 0.5-mm-thick A2017P-T3 and 0.6-mm-thick thermosetting CFRP thin sheets, an effective joining process was also proposed, named as "adhesive–embossing hybrid joining process". This joining method does not require any additional components and can eliminate holes that would cut the continuous carbon fibers and cause stress concentration. Hence, a smaller weight and a higher joining quality can be attained, especially for thin joining sections. Two types of CFRP sheets were used, *i.e.*, the A-type CFRP was with the cross lay-up $[0^0/90^0/0^0/0^0/90^0/0^0]$, while the B-type CFRP was with the quasi-isotropic lay-up $[0^0/60^0/120^0/120^0/60^0/0^0]$. The optimized embossing stroke and temperature were respectively 1.8 mm and100 ^{0}C (the holding time was about 10 s). Utilizing another A2017P sheet under the adhesively bonded specimen as a dummy sheet was one of the determinants of obtaining a sound hybrid joint without visible internal defects. The optimized sample placement for warm embossing (from top to bottom) was as follows: A2017P sheet, adhesive layer, CFRP sheet and dummy sheet. After the optimal embossing process, the maximum tensile shear load, displacement and static absorption energy of the adhesively bonded A2017P-CFRP (A-type) joint increased by 69.2%, 48.0% and 165.3%, while for the A2017P-CFRP (B-type) joint, the corresponding values were 89.3%, 40.9% and 152.9%. The adhesive–embossing hybrid joining process also exhibited a good applicability for the dissimilar joining combination of 0.3-mm-thick SUS304 and 0.6-mm-thick CFRP thin sheets.

The mechanical anchor effect of the embossed pit, the expansion of the adhesive area, the concentration of adhesive at the edge of the pit, the shrinkage and wrinkles of the CFRP sheet as well as the appropriate heating procedure were the main reasons for the improved joining quality. The negative effects of the hybrid joining method on the mechanical properties of the B-type CFRP sheet were severer than those in the case of the A-type CFRP sheet, owing to the lower formability of the former under the same embossing conditions. Thus, the adhesive–embossing hybrid joining approach was more suitable for joining A2017P-CFRP (A-type) thin sheets. The adhesive–embossing hybrid joining method has absolute advantages over rivet bonding and adhesive-rivet hybrid joining.

The adhesive–embossing hybrid joining process was extended to 0.5-mm-thick A2017P-T3 sheet and three types of 0.5-mm-thick GFRP sheet [*i.e.*, GFRP (cross), GFRTP (cross) and GFRTP (mat)]. Compared with the adhesive bonding method, the hybrid joining process exhibited superior joining performance for A2017P-GFRP (cross) single-lap joining combination, but not for A2017P-GFRTP (cross) and A2017P-GFRTP (mat) joining combinations. The applicability of the hybrid joining method was mainly determined by the deformation consistency between metallic and composite adherends. For the A2017P-GFRP (cross) hybrid joining, the optimized embossing stroke and temperature were 1.5 mm and 80 ^{0}C (the holding time is about 10 s), with a 0.6-mm-thick adhesive layer. After the optimal warm embossing, the tensile shear test results indicated that the maximum tensile shear load, displacement and absorption energy of the adhesively bonded A2017P-GFRP (cross) joint increased by 16.6%, 24.0% and 43.2%, respectively. After warm embossing, the ratio of tensile strength of joint to the GFRP (cross) sheet improved from 64.5% to 75.2%.

In addition to the mechanical anchor effect of the embossed pit, the additional friction and micro-anchoring effects caused by uncovered glass fibers in the inner layer of the GFRP (cross) sheet also appeared to contribute to the increased tensile shear load. The joining performances of the adhesive–

embossing hybrid joints were determined by the surface roughness of composites, the number of volumetric defects in the adhesive layer, the sensitivity to heating procedure and the deformation degree.

The investigation shows that the adhesive–embossing hybrid joining process is a competitive alternative joining method for the fabrication of ultra-lightweight thermosetting FRP-metal hybrid structures, and has great potential for wider applications, which is attributed to its benefits in terms of joining properties, operation simplicity, weight-cost effectiveness and recyclability. The further developments of the proposed hybrid joining process has a close independency on the fiber structural optimization, formability enhancement of FRP sheet and the developments of advanced adhesives.

To sum up, this doctoral dissertation proposed new joining processes for two joining combinations involving ultra-thin sheets: aluminum alloy-to-steel and aluminum alloy-to-thermosetting FRP. These promising and competitive joining processes are simple to operated, require no additional component, exhibit stable joining performance with high joint efficiency factor, long dwell time to separation loading and high absorption energy, as well as have great potential to be fully or partially automated. In the future, more developments of the proposed dissimilar joining processes by exploring more energy-effective heating procedure, further increasing the formability of the base joining materials, utilizing surface treatment to the joining sections and applying scale-up automation technologies would be of great industrial significance.