論 文 の 内 容 の 要 旨

論文題目

Investigation on bonding interface formation between dissimilar metallic materials by ultrasonic welding
(異種金属の超音波接合における接合界面形成の検討)

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In automotive and other transportation industries, steel has been the most important structural materials. To meet the requirement of weight reduction for reducing CO_2 emission, multi-material structure is gradually developed by combining steel with other materials. Conventional fusion welding techniques has limitations because fusion zone and heat-affected zone often lead to significant the formation of brittle intermetallic compounds (IMC) that degrade mechanical properties of the joints, and therefore, are considered difficult in the application of bonding steel and other lightweight metals. Thus, an alternative technique that can join steel and other materials at relatively lower temperature is desired. As the alternative joining technique, solid-state bonding technique is favorable. From that standpoint, ultrasonic welding (USW), a solid-state bonding technique, has attracted attentions because of advantages such as short welding time, relatively low bonding temperature, and less energy consumption.

Review of various aspects of USW had been conducted in Chapter 1, including interfacial phenomena, the effect of surface condition and steel hardness, and the use of interlayer metals. However, the relationship between bonding interface formation and bonding strength evolution, including bonding hard steel and other metals with different surface roughness or material hardness, investigation on the early stage before IMC formation, and the use of interlayer metals during USW process remain insufficient. Therefore, the objective of this study is to clarify bonding interface formation mechanism with its strength evolution from the early stage to achievement of bonding. Relationship between bonding interface formation and bonding strength evolution without (or with) interfacial reaction including the time-independent process, effects of surface roughness and steel hardness on the process, and effect of interlayer metals on bonding strength evolution and its interface formation are included.

In Chapter 2, relationship between formation of bonding interface and bonding strength evolution with steel and other dissimilar metals without interfacial reaction was investigated. In the development of bonding interface between Ni and IF steel, wear particles were firstly formed under the abrasion caused by clamping and oscillation of USW, increased with abrasion and subsequently flattened under the clamping force to form bonded sections with the vanishing of voids or gaps. As a result, intermixed bonding interface can be formed from flattened wear particles with sufficient bonding strength.

Regarding the effect of surface roughness on bonding interface formation and its strength evolution, the smooth mating surfaces could promote the fraction of contact areas to obtain a rapid increase of bonding strength. As mating surfaces became rougher, bonding formation could be more difficult by limited contact fraction between the base metals, and thus the occurrence of rapid increase of bonding strength could be delayed.

In the effect of steel hardness/microstructure on bonding interface formation and its strength evolution, Ni and soft steels (i.e. ferrite) were bonded with a rapid increase of bonding strength by inducing a higher degree of plastic deformation with flattened wear particles with good joint integrity compared with Ni and hard steel (i.e., martensite and pearlite). Also, it reveals that two wear modes occurred in the development of bonding interface at the early stage: wear particles formation as metals have similar hardness and attached metal fragments as metals have dissimilar hardness.

In Chapter 3, the evolution of bonding strength and microstructure at the bonding interface was investigated from the early stage before the formation of intermetallic compound in steel/Al and steel/Ti interfaces. In the development of bonding interface of IF steel and Al5052 alloy, adhesive wear occurred when steel and Al alloy have sliding contact, and thereafter, a thin layer of Al was attached onto the surface of the steel. As the welding time increased, bonding sections were gradually formed with the increase of interfacial temperature due to the sliding friction with softening of Al, and subsequently the voids or gaps between attached Al and the base metal were disappeared. The formation of an Fe-Al intermetallic compound was identified after 3.0 s of welding time.

In the development of IF steel/Ti bonding interface, attached steel or Ti fragments with adhesive wear to the opposite side were occurred at the early stage of USW. Under this condition, gaps between attached metals and the base metal limited the increase of bonding strength. As welding time increased to longer than 2.0 s, phase transformation of β-Ti occurred near bonding interface at a temperature above 600 ºC to contribute to extensive bonding formation due to increased deformability of β-Ti and IF steel at this elevated temperature. Subsequently, bonding was almost achieved after 2.5 s of welding time with a sufficient bonding strength.

In Chapter 4, the utilization of interlayer has been investigated in bonding dissimilar metals, steel and Ti. All species of interlayer had a positive influence on accelerating bonding strength evolution, and resulted in base metal fracture earlier than the case without interlayer. Al revealed a good enhancement on accelerating bonding strength evolution due to its good deformability and adhesive wear (galling) behavior to stick on IF steel and Ti in a short welding time. As a comparison, Zn exhibited a slower increase than Al interlayer due to time requirement for complete melting of Zn foil and formation of continuous IMC layers without voids. On the other hand, Ni was possessed the slowest bonding strength evolution because Ni required a longer welding time to form bonding by flattening wear particles at IF/Ni interface and more contact at Ni/Ti interfaces, and this difference can be contributed to high hardness of Ni. It is considered that good deformability (soft) and avoiding occurrence of melting to cause gap or voids distributed at bonding interface could be considered as important factors for increasing bonding strength evolution in bonding dissimilar metals.

According to the above, some factors were found to be relevant for the bonding interface formation with its strength evolution in bonding steel and other dissimilar metals by USW. Firstly, smooth and flat mating surfaces can assist the contact area formation to undergo bonding formation, and thus a rapid increase of bonding strength can be obtained. Secondly, in bonding steel and hard metals, the combination with similar hardness (i.e., Ni and steel) can induce a higher degree of plastic deformation by wear particles with abrasive wear to rapidly increase bonding strength. Lastly, in the combination of steel and soft metal (i.e. Al interlayer in bonding steel/Ti), attached metals with adhesive wear (galling of Al) can enhance contact fraction to form bonded areas extensively, leading to a rapid increase of bonding strength. Nevertheless, in the combination of hard metals (i.e., attached Ni fragments on martensite/pearlite), attached metal fragments contributed to longer welding time for bonding formation between attached metal fragment and base metal with low degree of plastic deformation, leading to slow increase of bonding strength. This difference could be attributed to the deformability of metals at elevated temperature during USW. In addition, intrinsic wear properties between dissimilar metals seems to significantly affect bonding formation at the early stage of welding (i.e., Al galling on steel and Ti).

For scientific aspect, this study provided a comprehensive understanding between bonding strength evolution with bonding interface formation process, where wear modes (wear particles and attached metal fragments) play an important role at the early stage of USW to affect the bonding strength evolution in bonding steel and other hard metals due to the difference of material hardness. Also, the understanding of surface condition confirmed that smooth and flat mating surfaces can assist bonding strength evolution with extensive contact points formation. As for bonding steel/Al and steel/Ti having possibility of interfacial reaction, attached metals with adhesive wear was identified as a significant interfacial phenomenon before the IMC formation, which is highly related to bonding strength evolution. In addition, the utilization of interlayer metals implied that soft metal without melting property could be advantageous for bonding strength formation by its deformability and wear behavior (i.e., Al) to enhance the contact fraction with rapid bonding formation.

For industrial aspect, this study provided the possibility and useful information of bonding steel and other dissimilar metals by USW for manufacturing multi-material structural materials of automobiles. For example, feasibility of joining high strength steels (martensite) and other hard metals by USW was confirmed in this study other than using diffusion bonding or conventional fusion welding. Further, understanding of wear modes based on hardness of metals can provide information for improving bonding strength evolution by selecting metals having similar hardness to induce more plastic deformation at bonding interface. Also, the utilization of interlayer metals can be provided as a potential solution for solid-stately bonding steel and other dissimilar metal that are difficult to be bonded (e.g. steel and Ti), and acceleration of bonding strength could be obtained by selecting proper interlayer metal in view of its deformability and wear properties.

Regarding the future perspective based on the above findings, some further research topics can be taken into account, for example:

1. Detailed observations at the bonding interfaces near wear particle or attached metal fragments by transmission electron microscopy technique to confirm the bonding formation mechanism in a small scale;
2. Modelling of bonding formation in a microscopic scale, focusing on deformation at the vicinity of bonding interface with increased temperature and enabling to predict the bonding quality; and
3. Prediction of bonding strength evolution based on the modelling of bonding formation with given parameters, such as clamping force, oscillation amplitude and welding time during USW.

Subsequently, a comprehensive understanding of bonding formation in microscopic scale including the above factors (temperature, oscillation, clamping force, time) is expected to be obtained based on both of modelling and experimental results.