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その他のタイトル	低温での金属固相接合における界面強度発現機構
学位授与年月日	2018-03-22
URL	http://doi.org/10.15083/00078085

博士論文（要約）

Mechanism of interfacial strength evolution in metal-to-metal solid-state bonding at low temperatures

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According to the recent global environmental problem and safety problems of the automobile and transportation industries, countless automobile parts were solely manufactured and combined together by joining processes to maximize the mechanical properties and minimize the overall weight of the vehicles. Therefore, material joining process has been used and researched. Recently, the solid-state bonding has been widely utilized due to their merits over traditional fusion welding: absence of hazardous heat affected zone (HAZ). Nevertheless, the solid-state bonding at relatively high temperatures potentially provides several disadvantages, for examples, composition degradation, brittle intermetallic formation, grain growth, etc. Accordingly, solid-state bonding at low temperatures is preferred.

In chapter one, several hypotheses of the solid-state bonding, describing the evolution of interfacial strength, had been reviewed. It was found that high temperature or deformation is required for good bonding strength, however the description of the evolution of the bonding strength with isothermal holding time and the dominating mechanisms at the early stage of solid-state bonding at low temperatures are unclear. Therefore, the objective of the thesis is to clarify the dominant mechanism in the early stage of evolution of interfacial strength of solid-state bonding at low temperatures between similar and dissimilar metal constituents without intermetallic compound formation with investigation from macroscopic scale to atomic-scale and to determine the effects of several parameters on the evolution of interfacial strength in the early stage.

In chapter two, the evolution of the microstructure and interfacial strength of specimen of steel/steel interface, bonded by hot pressing and subsequent isothermal holding was examined experimentally and numerically. It was found that the evolution of interfacial strength involves two stages: the first stage starting immediately after the compression with rapid increase in interfacial strength, and the second stage, when the interfacial strength slowly increases. The as-compressed interface possesses low strength, then the interfacial strength tended to increase at the contact area without effect from long-range diffusion. In addition, the short-range atomic rearrangement was observed at the bonding interface in the first stage. In contrast to the first stage, the evolution of interfacial strength in the second stage seemed to be attributed to the long-range diffusion, in the other words, the increase in contact area.

The increase in interfacial strength in the first stage was found to be significant at the deformed contact area. Consequently, the effects of the compressive strain on the evolution of interfacial strength in the first stage of solid-state bonding of specimen of steel/nickel interface at low temperature was investigated in chapter three, based on the interface facture of embedded process zone (EPZ) model. It was found that the increase in interfacial strength in the first stage was greatly affected by plastic energy dissipation during the interface fracture, which is closely related to the residual strain at the microstructure near the interface on the steel side. The deformation induced by the compression significantly decreased in the first stage, leading to decrease in yield stress of the microstructure near the interface on the steel side and consequently increase in plastic energy dissipation around the crack tips during interface fracture.

In chapter four, the effects of the compressive strain on the evolution of the intrinsic strength of the interface was investigated using MD simulation. The intrinsic strength of the interface was evaluated by uniaxial tensile loading perpendicular to the interface. The results revealed that the intrinsic strength of the interface is low under an as-compressed condition and tends to continuously increase as isothermal holding time increased. The existence of disordered atoms layer near the interface induced by the compression contributed to weak intrinsic strength under an as-compressed condition, because the fracture tended to initiate and propagate through the layer. As the isothermal holding time increased, the short-range atomic rearrangement continuously occurred, leading to significant decrease in potential energy and increase in intrinsic strength of the interface.

To further clarify the mechanisms in the first stage of evolution of interfacial strength of the solid-state bonding at low temperatures, the relationship between energy release rate, yield stress near the interface on the steel side and the intrinsic strength of specimen of steel/steel, steel/nickel and steel/molybdenum interfaces during interface fracture was investigated by numerical simulation using finite element method with EPZ model and cohesive zone model (CZM) as the interface. The results show that energy release rate during interface fracture is relied mutually on the yield stress near the interface on the steel side and the intrinsic strength. In addition, the constitute equation was constructed based on the principal stress distribution in front of the crack tips of elastic-plastic fracture mechanics by fitting with the numerical simulation results under range of yield stresses of each combination of interfaces above the value of yield stress near the interface on the steel side at the end of the first stage in the experiments. The result revealed that the energy release rate significantly increases as the yield stress near the interface on the steel side decreased as appeared in the experiment, when the intrinsic strength of the interface are still small compared to the theoretical strength. The evolution of the energy release rate of specimen of steel/molybdenum interface was found to significantly longer than that of specimen of steel/steel and steel/nickel interfaces, respectively, because of the constant high yield stress of constituent of molybdenum, in the other words, the limitation of plastic dissipation on the molybdenum on the steel side during the interface fracture.

According to the above studies, the mechanism during the first stage of the solid-state bonding at low temperatures of similar and dissimilar metal constituents was investigated and it was found that the yield stress of the microstructure within a few micrometer from the interface greatly affects the interfacial strength, when the intrinsic strength of the interface is significantly lower than the theoretical strength in the first stage. In addition, the compressive strain, the bonding temperature and the properties of the constituent metals are essential parameters affecting the behavior of the evolution of interfacial strength in the first stage of solid-state bonding at low temperatures. Therefore, this research aimed to provide fundamental understanding of the solid-state bonding at low temperatures of metals in order to improve performance of welding process at low temperatures and short time.