Grain Structure and Texture Evolution in Aluminum and Magnesium Alloys During Friction Stir Welding (アルミニウムおよびマグネシウム合金の摩擦攪拌接合過程における 結晶粒組織と集合組織形成機構)

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論文内容要旨

The increasing demand for reduction of exhausting gases emission, better fuel efficiency and higher operation efficiency in transportation applications is prompting extensive research into light weight structural materials. Magnesium (Mg) and aluminum (Al) alloys, being the lightest metallic materials in practical use, offer a great potential for weight saving in today's vehicles. The promising balance of physical and technological properties of these materials makes them particularly attractive for automotive and aerospace industries. However, poor weldability and low formability significantly restrict widespread application of these materials.

The expected escalation in the use of these materials only emphasizes the importance of providing viable joining technique and of increasing formability of these materials. Therefore, friction stir welding (FSW) appears to be a promising processing technique for broadening the industrial application of these materials. As a solid-state process, FSW avoids solidification problems associated with conventional fusion welding, and thus enables to produce high-quality welds with excellent mechanical properties. Moreover, intense plastic deformation in FSW drastically refines grain structure and principally changes crystallographic texture in the materials, and thus would improve their formability.

Since the microstructure developed during FSW strongly affects the service properties, it is of critical importance to clearly understand how the microstructure develops during the welding process. Therefore, a number of research efforts were undertaken recently in an attempt to clarify this issue. Presently, the most studies in this field have been focused on FSW of Al alloys. It is well known that formation of the fine-grained microstructure in the stir zone (SZ) is attributed to dynamic recrystallization (DRx), and the DRx process is found to be continuous in nature arising from gradual rotation of grain orientation in some cases. Nevertheless, some important details of the grain structure evolution during FSW of Al alloys have been still unknown.

On the other hand, much less attention has been given to hcp metals, such as Mg alloys, despite their significant industrial-importance. Typically, the microstructural examinations in the FSWed Mg alloys have been focused on a characterization of final grain structure developed in the SZ, but not on the microstructure evolution itself, i.e., it has been completely unclear how this microstructure develops during the welding process.

FSW is characterized by frictional heating and plastic flow arising from the rotating tool. Many researches have been applied to clarify the material flow during FSW. Recently, electron backscatter diffraction (EBSD) technique has been used to interpret the crystallographic texture developed in the SZ. The material flow during the FSW process is crystallographic in nature, and thus should lead to significant textural changes. By analyzing the microtexture distribution, therefore, it would be possible to deduce the material flow during FSW. These observations have shown that the material flow during FSW may arise from (i) shearing along pin column surface (this is the most typical case), (ii) shearing along shoulder surface (usually observed in the top part of the SZ) and (iii) combined deformation induced by the pin and shoulder.

Therefore, the objective of the present study is to clarify the microstructure and texture evolution during FSW of automotive Al and Mg alloys. FSW was applied to 6016 aluminum and AZ31 magnesium alloys. In order to provide fundamental insight into microstructure evolution during FSW, "stop-action" technique was employed to preserve the dynamic features of the material flow. Grain structure formation and texture evolution during FSW were analyzed by using high-resolution EBSD technique. The obtained results are summarized as follows.

In this study, commercial 6016 Al and AZ31 Mg alloys with a nominal chemical composition, 2 mm in thickness, were used. The as-received sheets were butt-welded parallel to the rolling direction at various welding parameters and different tool shoulder diameter. During FSW, the welding tool was tilted by 3° from the plate normal. In order to provide the "stop action" experiment, the welding machine was emergency stopped during the welding process, the welding tool was rapidly retracted from the tool keyhole, and the material near the final tool position was immediately quenched.

In Al alloy, with increasing strain in region ahead the tool keyhole, the parent grains tended to be sheared in the direction toward the tool rotation probably due to geometrical requirements of the imposed strain. Low angle boundaries (LABs) started to form in the grain interior, and thus LAB fraction rapidly increased.

In region close to the pin, the parent grain became more elongated toward the tool rotation with higher aspect ratio as the strain increased. Then, the parent grains were extremely drawn out, becoming thin fibrous grains as the strain dramatically increased. Simultaneously, the deformation-induced boundaries in this area rapidly accumulated high-angle misorientation; this broke up the elongated parent grains into strings of relatively low-aspect ratio grains. The increased temperature induced local grain boundary migration, thus leading to formation of bulges along grain boundaries. Finally, fine equiaxed grain structure formed in the region close to the pin.

In region directly behind the pin, the structure morphology, such as average grain size and texture of the material, was broadly similar to that observed ahead the pin. With increasing the distance from the pin, however, the grain orientation significantly changed. This indicates that the microstructure formed by the rotating pin was not final, and that the material behind the pin experienced additional deformation and heat input.

Meanwhile, during FSW of Mg alloy, the grain structure evolution was different from that of Al alloy. An increase in strain led to many deformation twin boundaries in the parent grains. In region closer to the pin, small equiaxed grains started to nucleate along original grain boundaries, thus producing "necklace-type" microstructure and then gradually consumed the parent grains. Directly near to the tool keyhole, the newly developed fine grains became a dominant microstructural feature consuming almost completely the remnants of the original grain structure. The formation of the "necklace-type" microstructure along the original grain boundaries would play a dominant role in the microstructure evolution of AZ31 magnesium alloy during FSW. The nucleation of fine equiaxed grains along the original grain boundaries was driven by discontinuous and continuous recrystallizations.

Grain structure, such texture and grain size, in region directly behind the tool was roughly similar to that observed ahead the pin. With increasing the distance from the pin, the grain structure showed notable re-orientation coupled with the notable increase in LAB fraction. These observations revealed that the material in these regions had experienced additional deformation induced by the shoulder.

In attempting to understand the material flow during FSW, the microtexture distributions in regions ahead and behind the tool keyhole were analyzed. It was shown that the texture development was a complex process consisting of several stages. The material was initially deformed by the rotating tool pin, which led to shear plane roughly parallel to the pin column surface. Thus, it was reasonably assumed that the material flow in this region mainly arose from the pin. The material then experienced another deformation associated with the combined effect of the pin and shoulder. The shear plane was approximately along the truncated cone having a diameter close to the tool shoulder diameter in top part of the SZ and the pin diameter in the bottom part of the SZ. Finally, the material might experience further deformation induced by the rotating tool shoulder, which resulted in the shear plane approximately parallel to the shoulder surface.

The global pattern of the microstructure evolution during FSW of Al alloy indicated that the grain development process would not only be mainly driven by grain subdivision process, but also involved geometric effects of strain and high angle grain boundary migration.

Meanwhile, in the Mg alloy, the grain structure formation was established to be mainly governed by the continuous and discontinuous grain nucleation at original grain boundaries. It was also demonstrated that the material experienced another deformation by edge of the shoulder in the regions behind the pin.

The texture formation during FSW in Al alloys was strongly affected by shoulder diameter as well as FSW parameters (welding and rotational speeds). Small shoulder diameter produced the weld with final microtexture having shear plane approximately along the truncated cone. An increase in shoulder diameter increased a contribution of the tool shoulder, which led to shear plane roughly parallel to the shoulder surface. The contribution of the shoulder increased with decreasing travel speed as well as increasing rotational speed.

On the other hand, in Mg alloys, it was demonstrated that the texture formation during FSW did not depend principally on the shoulder diameter as well as FSW parameters (welding and rotational speeds) in the range of the welding parameters used in this study.

論文審査結果の要旨

摩擦攪拌接合は、アルミニウム合金などを用いた輸送機器の実機製造等に用いられる固相接合法である。接合中、接合部には不均一な集合組織分布を有する微細等軸結晶粒が生成し、接合部の諸特性に影響を及ぼす。接合部の高性能化・高特性化には接合過程での微細結晶粒および集合組織の形成を制御する必要があるが、これらの形成機構に関する基礎的知見はほとんど得られていない。本研究では、板厚 2mm のアルミニウム合金とマグネシウム合金の摩擦攪拌接合過程での微細結晶粒ならびに集合組織の形成機構をストップアクション法と EBSD 法により明らかにすることを目的としている。論文は全編５章で構成されている。

第１章は序論であり、本研究の背景および目的を述べている。

第２章では、アルミニウム合金とマグネシウム合金の接合過程での組織変化を凍結し、微細結晶粒組織の形成機構を調べている。接合ツール前方での組織変化を解析し、アルミニウム合金においては結晶粒サブディビジョンに代表される連続再結晶が、マグネシウム合金においては連続再結晶に加えて不連続再結晶が生じている可能性を示している。また、接合ツール後方での組織解析により、ツールピンによる変形後にショルダによる変形が起こっていることを明らかにしている。

第３章では、アルミニウム合金の接合過程での集合組織形成機構を調べている。集合組織形成は、ツールピン近傍ではピン表面に沿ったせん断変形に支配されるが、ピンから離れるに従って、ショルダ表面に沿ったせん断変形へ徐々に遷移することを示している。せん断面の遷移は接合中の熱影響が大きいほど顕著になることを示している。

第４章では、マグネシウム合金の接合過程での集合組織形成機構を調べている。集合組織形成を支配する変形は、アルミニウム合金と同様であり、ピン近傍でのピン表面に沿ったせん断変形からショルダ表面に沿ったせん断変形へ遷移することを示している。

第５章は本研究の結果をまとめた総括である。

以上要するに本論文は、アルミニウム合金およびマグネシウム合金の摩擦攪拌接合過程での結晶粒組織ならびに集合組織形成機構を明らかにしたものであり、材料システム工学の発展に寄与するところが少なくない。

よって、本論文を博士（工学）の学位論文として合格と認める。