Microstructure and Joint Strength of Steel/Steel and Steel/Light-Metal Friction Bit Joints

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学位授与年月日	平成２１年９月９日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）材料システム工学専攻
学位論文題目	Microstructure and Joint Strength of Steel/Steel and Steel/Light-Metal Friction Bit Joints (鋼同士および鋼/軽金属異材の摩擦ビット接合におけるミクロ組織と接合強度)
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論文内容要旨

Recently, automakers have been attempting weight reduction as a key strategy in developing fuel-efficient vehicles. To achieve this strategy, many new high performance light-weight structural materials, such as aluminum (Al) alloys, magnesium (Mg) alloys and advanced high strength steels (AHSS), are used to the manufacturing of automotive structures. The use of these materials presents challenges of formability and weldability, because AHSS has higher contents of alloying elements than lower strength steels and because light metals cannot easily be joined to AHSS by traditional spot welding technologies. In order to resolve some difficulties of spot joining of AHSS and dissimilar combinations between AHSS and light metal, a new concept, friction bit joining (FBJ), has been developed, where a consumable joining bit is used for joining of two or more sheets. FBJ can be classified into four steps: cutting step, joining step, cooling step and retracting step. The process relies on a cutting step in which the bit cuts through the top layer (or layers) of material, followed by a joining step in which the bit and surrounding sheet materials are heated by friction, then the bit is consumed as filler material that joins the sheets together. The schematic drawing of this process is shown in Fig. 1.

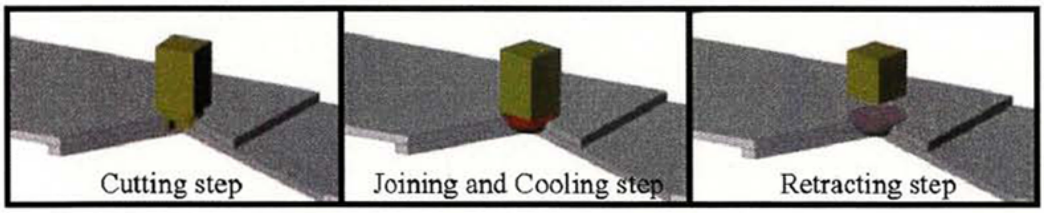

Fig. 1 Schematic illustration of FBJ process

Previous studies of FBJ focused on the process development since the technology only recently began to be studied. However, the relationship among welding parameters, microstructure and mechanical properties has not been examined in the FBJ welds. In the present research, similar joining of steel/steel and dissimilar joining of Al/steel and Mg/steel were conducted using FBJ process. The parameter effects on lap shear strength (LSS) and microstructure evolution in the joint were systematically investigated to achieve a better understanding of the feasibility and joining mechanism of this brand new joining technique.

Chapter 1 gives a brief introduction of the research background, motivation and objectives of the present thesis work.

In Chapter 2 "Feasible study on friction bit joining of steel/steel", parameter effect on LSS of DP980 steel joint produced by FBJ is systematically investigated. The results show that DP980 could be acceptably welded under proper welding parameters. It is confirmed that the cutting speed significantly influences the actual plunge depth of bit and thus affects joint strength. Using optimal FBJ parameters, acceptable welds with reasonably high LSS (16.2 kN, average of three samples) could be obtained. Moreover, microhardness distributions of the cross sections of the joints indicate that softening caused by heat-input during FBJ is contributed to the weld failure.

In Chapter 3 "Microstructural evolution during friction bit joining of steel/steel", microstructure evolutions of two joints welded at different cutting speed are investigated. The hardness profiles could be correlated with the microstructure distribution in the joint, and microstructural evolution of each region could be reasonably explained by solid-state phase transformation during the cooling cycle of FBJ. The results show that the lower temperature during FBJ results in tempering of the bit without any phase transformation which enables the bit to plunge into the sheet materials deeper which is an effective way to obtain high LSS.

In Chapter 4 "Microstructure and joint strength of steel/light-metal friction bit joints", feasibility study on FBJ of DP980 steel to AA5754 Al alloy using a bit made of 4140 steel is conducted. Systematical parameter study reveals parameter effects on LSS. The LSS is strongly affected by the joining parameters, and the high LSS could be obtained by the higher mechanical locking of aluminum alloy by the bit and the high degree of metallurgical bonding between the bit and the bottom DP980 steel sheet. Maximum LSS of 6.9 kN is obtained using optimal joining parameters under the present experiment conditions. Furthermore, microstructure of the joint is clarified. Both enlarging consolidation area at bit/DP980 interface and minimizing cracks in the bit is an effective way to obtain high LSS. Cracks are caused by differences of microstructure between the upper part of the bit and the lower part during FBJ. It is thought that bit can be heat-treated with a higher hardness to avoid cracking. Finally, feasibility study on FBJ of DP980 steel to AZ31 Mg alloy is conducted. Systematical parameter study reveals parameter effects on LSS. It is found that the LSS of the joint slightly depends on the welding parameters. High LSS joints could be created in a wide range of parameters sets. Even at very high plunge rate, a relative high average LSS of 5.7 kN could be obtained. This implies that FBJ could be more efficient when applied to joining of Mg alloys to steel.

Chapter 5 consists of conclusions of each chapter. From the above mentioned studies, the following general conclusions can be obtained.

(1) Steel/steel, Al/steel, and Mg/steel can be joined by FBJ, which produced high level strength compared with conventional spot welding. The strength comes from the bonding between the bit and the bottom steel sheet. Microstructural changes of the bit and the bottom sheet are important to the weld quality.

(2) Microstructures of the various weld regions are associated with the local thermo-mechanical cycles and peak temperatures reached during FBJ.

(3) Strength of the joints welded by FBJ can be correlated to microstructure distribution across the weld. It suggests that the mechanical properties can be modified through microstructure control.

論文審査結果の要旨

摩擦ビット接合は消耗ツールを用いた新しい点接合技術であり、（１）刃先を有する鋼製消耗ツールによる穴あけ過程、（２）消耗ツールと被接合材の摩擦接合過程、（３）消耗ツールの切断過程　から構成される。本接合は、高強度鋼板の同種接合や軽金属板／高強度鋼板の異種接合が可能であり、車体のマルチマテリアル化への転換が必須となっている自動車産業において注目されているが、高強度鋼同種接合部および軽金属／高強度鋼の異種接合部における接合条件、諸特性と接合部組織の関係に関する基礎知見はほとんど得られていない。本研究では、車体構成材として利用拡大が期待される９８０ＭＰａ級高張力鋼、アルミニウム合金、マグネシウム合金を用いて、高張力鋼の同種接合ならびに鋼／軽金属の異種接合を行い、得られた接合部の継手引張せん断強度に及ぼす接合条件の影響と材料組織学的な強度支配因子を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、９８０ＭＰａ級高張力鋼同種接合部の引張せん断強度に及ぼす接合条件の影響と強度を支配する組織因子を調べている。高張力鋼同種接合部の場合、強度は接合初期の穴あけ過程における消耗ツール回転速度に最も敏感であることを明らかにしている。また、引張破断は硬さが最も低いところを進展し、進展経路が長くなるほど強度が高くなることを示している。

第３章では、９８０ＭＰａ級高張力鋼同種接合部における組織形成機構を調べている。接合部内の組織分布は、接合過程での最高到達温度により説明でき、最軟化部は接合中にＡ１点以下の温度への加熱により、母材の島状マルテンサイトが焼戻されていることを明らかにしている。

第４章では、鋼／アルミニウム合金および鋼／マグネシウム合金の異種接合部での引張せん断強度に及ぼす接合条件の影響について主に述べている。異種接合部では、強度は摩擦接合過程での消耗ツール回転速度に支配され、消耗ツール／鋼間の接合面積と消耗ツール内に形成するクラックサイズの関係により継手強度が説明でき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、摩擦ビット接合における接合条件、継手強度と接合部組織の関係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。